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Skill and Working Memory

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A theory of skilled memory is proposed in which the size of working memory expands as skill increases. It is proposed that knowledge states in long-term memory are tagged to the current context and retrieved directly and rapidly for use in working memory. Evidence in the role of long-term knowledge structures in working memory is reviewed in several domains: (1) A memory span expert, (2) A mental calculation expert, and (3) A waiter with mnemonics skills.

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Why is memory so much better for skilled people in their domain of expertise? Our interest in this problem first began three years ago. when we started training a subject on the digit- span task. Over the course of two years of practice, our subject was able to increase his digit span from 7 digits to over 80 digits, and it was our analysis of this subject that led us to our interest in memory performance of skilled individuals. In this paper, we will first review the literature on skilled memory, then we will describe our analysis of skilled memory in the digit span task, and finally we will discuss our latest work with a mental calculation expert, a waiter who memorizes food orders, and we will discuss extensions of our work with normal subjects.

1. The Skilled Memory Effect

1.1. Short-Term Memory Capacity

The capacity of short-term memory has long been accepted as one of the most fundamental limits in people's ability to think, solve problems, and process information in general (Miller, 1956; Newell & Simon, 1972). The memory span (about 7 unrelated symbols) is the most accepted measure of short-term memory capacity (Miller, 1956), and this severe limit on readily accessible symbols is commonly taken as a fundamental limit on the working memory capacity of man's information-processing system (Baddeley, 1976; Klatzky, 1980). That is, recent events attended to in the environment, knowledge states activated from long-term memory, and intermediate computations necessary for performing complex information processing tasks are assumed to be held in short-term memory for immediate access. Working memory is equated with short-term memory, and it is this severe constraint on the number of readily accessible symbols that limits our information-processing capacity. Memory span has even been taken by some people as a fundamental measure of intelligence (Bachelder & Denny, 1977a,b). The superior memory performance by experts in their area of expertise seems to fly in the face of these basic limits.

1.2. Chess and Other Game Skills

The skilled memory effect has been in the literature for some time. de Groot (1966) discovered that chess Masters have virtually perfect recall of a chess board after viewing it for only a few seconds (5-10 sec), whereas novices can recall only 3 or 4 pieces (Chase & Simon, 1973a). Chase and Simon (1973a) showed that this memory is specific to the Master's knowledge domain by presenting chess players with randomized chess positions and finding that recall was uniformly poor for all players, regardless of their skill level. In addition to the Master's superior memory for chess positions, Chase and Simon (1973b) also found that the Master has greatly superior memory for sequences of moves.

According to Chase and Simon (1973b), this memory performance is the result of a vast knowledge base that the Master has acquired through years of practice. This knowledge includes procedures for generating moves, stereotyped sequences of moves, and stereotyped patterns of pieces. In order to explain the Master's superior memory for positions, Chase and Simon suggested that the Master recognizes familiar patterns that he sees often in his study and play, whereas the novice is able to notice only rudimentary relations in the limited time allowed in the chess memory task. When Chase and Simon (1973a) measured memory performance in terms of patterns rather than individual pieces, Master and novice memory performance were much more similar, and the absolute magnitude of memory performance was closer to 7. They concluded that the limit in performance in the chess memory task is due to the limited capacity of short-term memory. The Master holds retrieval cues in short- term memory for 7 patterns, located in long-term memory, and at recall, these cues are used to retrieve each pattern, one at a time from long-term memory. The novice, on the other hand, must utilize all of his short-term memory capacity to store the identity, color and location of 3 or 4 individual chess pieces.

There was one discrepant finding in the Chase and Simon (1973a) study which, in retrospect, seems critical to our analysis of skilled memory. They found that even when the Master's memory performance was scored in terms of patterns recalled, and the sophisticated guessing strategies of the Master were discounted, the Master's recall still often exceeded the accepted limits of short-term

memory capacity (7±2). In short, the Master's recall of *patterns* even exceeded the capacity of short-term memory, and Chase and Simon (1973b) were unable to fully explain this phenomenon. Charness (1976) later demonstrated that these chess patterns (i.e., their retrieval cues) are not retained in short-term memory because they are not susceptible to interference effects in short-term memory. Later, we will try to show that this result is perfectly compatible with our new conception of working memory.

This skilled memory effect has been replicated many times (Charness, 1976; Chi, 1978; Ellis, 1973; Frey & Adesman, 1976; Goldin, 1978, 1979; Lane & Robertson, 1979), and the same effect has been found with expert players in the games of go, gomoku and bridge. Reitman (1976) studied a professional-level go player whose perceptual memory for go patterns closely paralleled that of chess Masters for chess positions. In another study, Eisenstadt and Kareev (1975) compared recall of go and gomoku patterns. They took advantage of the fact that go and gomoku are played on the same 19 x 19 board with the same black and white stones, but the objects of the games are different and the types of patterns are different. In go, the object of the game is to surround the opponent's stones, whereas in gomoku, the object is to place 5 stones in a row. They trained subjects to play both games, and then, in one experiment, they asked subjects to recall a go position and a gomoku position. In actual fact, subjects were shown the same pattern, except that it had been rotated 90° and the color of the pieces had been reversed so that subjects were unaware of the structural identity of the positions. The interesting finding of this study was that when subjects thought they were recalling a go position, their recall of go patterns (i.e., stones crucial to the analysis of the position as a go game) was far superior to their recall of gomoku patterns (by a factor of almost 2 to 1), and when subjects thought they were recalling a gomoku position, their recall favored the gomoku patterns by almost a 2 to 1 margin.

Rayner (1958), in an interesting training study, was able to trace the development of gomoku patterns with practice. By studying a group of people over a 5-week period as they acquired skill in the game of gomoku, Rayner (1958) was able to describe the types of patterns that players gradually

learned to look for, and the associated strategies for each pattern. The patterns themselves are quite simple; the difficulty in learning the patterns arises from the number of moves required to generate a win from the pattern. The most complicated strategy that Rayner described was an 11-move sequence starting from a fairly simple and innocuous-looking pattern of four stones. In his analysis of the acquisition of gomoku, Rayner (1958) described a process by which his subjects gradually switched from an analytic mode of working through the strategies to a perceptual mode in which they searched for familiar patterns for which they had already learned a winning strategy. In short, Rayner (1958) analyzed in his laboratory over a 5-week period, the perceptual learning process in a microcosm that is presumed to occur on a much larger scale, over the course of years of practice, as chess players gradually acquire Master-level proficiency.

The skilled memory effect has also been found in the game of bridge, for which there is no obvious spatial component. Charness (1979) and Engle and Bukstel (1978) have both reported that high-level bridge experts can remember an organized bridge hand (arranged by suit and denomination) almost perfectly after viewing it for only a few seconds, whereas less experienced bridge players show much poorer recall. With unorganized hands, performance is uniformly poor for both experts and less experienced players. In addition, bridge experts were able to generate bids faster and more accurately, they planned the play of a hand faster and more accurately, and they had superior memory for hands they had played. Thus, it is our contention that bridge expertise, like chess, depends in part on fast-access pattern recognition because patterns are associated with procedural knowledge about strategies and correct lines of play.

1.3. Non-Game Skills

The skilled memory effect has also been demonstrated in domains other than games, such as visual memory for music (Salis, 1977; Slaboda, 1976). An additional important property of skilled memory has emerged from several of these non-game skill studies: hierarchical knowledge structures. Akin (1980) has analyzed the recall of building plans by architects and found several interesting results. First, as with chess players, architects recall plans pattern by pattern. Second,

architectural plans are recalled hierarchically. At the lowest level in the hierarchy, patterns are fairly small parts of functional spaces, such as wall segments, doors, table in a corner, etc. The next higher level in the hierarchy contains rooms and other areas, and higher levels contain clusters of rooms or areas. The fairly localized property of architectural patterns at the lowest level in the hierarchy is reminiscent of the localized nature of chess patterns reported by Chase and Simon (1973a). It is only at the next level in the hierarchy that architectural drawings take on the functional form of the architectural space: rooms, halls, etc. It seems that architectural patterns are similar to chess patterns in that functional properties are more important at higher levels while structural properties are more important at lower levels.

Egan and Schwartz (1979) have found superior recall of circuit diagrams by expert electronics technicians after a brief exposure (5-15 sec) of the diagram. Egan and Schwartz have also found evidence of a higher-level organization for the skilled electronics technician. At the lowest level, the basic patterns were very similar to the chess patterns and architectural patterns in terms of their localized nature. The skilled technicians, however, were faster and more accurate in their between-pattern recall than the novices, which is good evidence for the existence of higher-level organization. Egan and Schwartz concluded that expert technicians use their conceptual knowledge of the circuit's function to aid in their recall.

In the domain of computer programming, Shneiderman (1976) presented a printout of a simple FORTRAN program or a scrambled printout of a simple FORTRAN program to programmers with varying degrees of experience. The number of perfectly recalled lines of code from the real program increased dramatically with experience whereas there was virtually no increase in recall with the scrambled program; for the most experienced programmers, there was a 3 to 1 difference in recall (6 vs 18 lines). McKeithen, Reitman, Rueter and Hirtle (1981) have since replicated this result with ALGOL programs. Shneiderman (1976) further showed that the nature of the errors by the experienced programmers--replacing variable names and statement labels consistently, changing the order of lines when it did not affect the program's result--provided evidence that the experienced

programmers were using knowledge of the program's function to organize their memory for lines of programming code.

The existence of higher-level functional knowledge in the more experienced individuals has also been demonstrated in baseball fans. Chiesi, Spilich, and Voss (1979) have found that the differential recall of baseball events by individuals with high and low baseball knowledge can be traced to their differential ability to relate the events to the game's goal structure. That is, high and low knowledge individuals were equally competent at recalling single sentences of baseball information. However, high-knowledge individuals were better at recalling sequences of baseball events, presumably because they were better able to relate each sequence to the game's hierarchical goal structure of advancing runners, scoring runs, and winning.

A very similar result on normal subjects has been demonstrated by Bransford and Johnson (1973) for recall of paragraphs. Bransford and Johnson showed that subjects were better at recalling ideas from a paragraph if they were given an organizing principle for the paragraph at the time of learning, such as a title, an illustration of the main idea of the paragraph, or the topic of the paragraph. We would suggest that recall is facilitated by the use of some abstract hierarchical organizing structure for the paragraph. The same must be true of scripts and schemas as organizing structures for stories and scenes (Biederman, 1972; Bower, Black & Turner, 1979).

Although we will discuss this topic more fully when we discuss the analysis of our mental calculation expert, we briefly note here that mental calculation experts, as a side- effect of their computational skill, generally exhibit a digit span that is two or three times larger than normal (Hatano & Osawa, 1980; Hunter, 1962; Mitchell, 1907; Müller, 1911).

To sum up the analysis so far, the skilled memory effect has been demonstrated in a variety of game-playing and non-game- playing domains, although the bulk of the research has been centered on exceptional memories of chess Masters. In theory, this exceptional memory performance has been attributed to the existence of [illegible] term knowledge base built up by the expert with years

of practice. In game-playing domains this knowledge takes the form, in part, of patterns which serve the purpose of retrieval aids for desirable courses of action. It was suggested that in other domains, hierarchical knowledge structures exist in the expert for the purpose of organizing knowledge. For architectural drawings, functional areas (e.g., rooms) serve to organize lower-level structures (walls, furniture, etc.); for circuit diagrams and computer programs, function is used to organize the components; and for baseball games, the hierarchical goal structure of the game is used to organize sequences of events. Although Chase and Simon (1973a,b) did not find very much evidence for the existence of hierarchical structure in the Master's memory of chess positions, we suggest that there must indeed be some organizing principle to account for the fact that the Master's recall of *patterns* exceeds his short-term memory capacity. We will come back to this problem again later.

Finally, Before we get into the analysis of our digit-span expert, we should briefly mention a distinctly different but related type of memory expert: the mnemonist. Unlike the skill-based expert, the mnemonist does not achieve his exceptional memory performance in a particular area of expertise. Rather, the mnemonist has acquired a system or repertoire of techniques for memorizing nonsense material. Persons with trained memories can use mnemonic techniques to memorize long lists of words, names, numbers and other arbitrary items. The most common technique of the mnemonist is the use of visual images as mediating devices, and the most powerful system is the method of loci, in which items to be remembered are imagined in a series of well-memorized locations interacting with objects in these locations. Mnemonists have generally made themselves known as stage performers, although the techniques have received a great deal of attention recently in the psychological literature. A cognitive theory of exceptional memory should deal with both the expertise-based memory performance and the mnemonics-based memory performance. We will return to the cognitive principles underlying mnemonics in a later section. (See Bower, 1972, for a good scientific analysis of mnemonic techniques, Yates, 1966, for a good historical analysis, and Lorayne and Lucas, 1974, for the current best-selling system.)

2. Analysis of a Memory Span Expert

In this section, we will describe the highlights of our previous analysis of digit span experts (reported more fully in Chase & Ericsson, 1981; and Ericsson, Chase & Faloon, 1980), and in addition we report some new results of interest to our theory of skilled memory.

2.1. The Effects of Practice on Digit Span

The basic procedure in the memory span task is to read digits to subjects at the rate of 1 digit per sec, followed by ordered recall. If the sequence is reported correctly, the length of the next sequence is increased by one digit; otherwise the next sequence is decreased by one digit. Immediately after the recall of each trial, subjects are asked for a verbal report of their thought processes during the trial. At the end of each session, subjects are also asked to recall as much of the material as they can from the session. On some days, experimental sessions are run instead of practice sessions.

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Insert Figure 1 about here

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Figure 1 shows the average digit span of two subjects as a function of practice. Both subjects demonstrate a steady, although somewhat irregular increase in digit span with practice. It appears that 200-300 hours of practice is sufficient to yield performance that exceeds the normal memory span by a factor of 10. Our original subject, SF, began the experiment in May 1978 and continued for two years (a total of 264 sessions) before the experiment ended[1]. The highest digit span performance achieved by SF was 82 digits. We started training our second subject, DD, in Feb. 1980 to see if it was possible to train another person to use SF's system, and now, after 286 sessions, the highest span achieved by DD is 68 digits. Until now, the highest digit spans reported in the literature have been around 20 digits, and these have generally been achieved by mental calculation experts (Hatano & Osawa, 1980; Hunter, 1962; Martin & Fernberger, 1929; Mitchell, 1907; Müller, 1911).

How is this memory feat possible? To answer this question, we have resorted to an extensive

analysis of our subjects' verbal reports, we have conducted over a hundred experimental procedures of various kinds on our two subjects, and we have even written a computer simulation model of SF's coding strategies. In the process, we have discovered three principles of memory skill that we believe characterize the cognitive processes underlying this memory skill: (a) subjects use meaningful associations with material in long-term memory, (b) subjects store the *order* of items in another long-term memory structure that we have called a "retrieval structure", and (c) subjects' encoding and retrieval operations speed up with practice. We consider each of these in turn.

2.2. Mechanisms of Skilled Memory

2.2.1. The Mnemonic System

When we first started this experiment, we simply wanted to run a subject for a couple of weeks to see if it was possible to increase the memory span with practice, and if so, could we use the subject's retrospective reports to figure out how it happened. The verbal reports turned out to be very revealing of both the mnemonic system and the retrieval structure.

The first four hours of the experiment were fairly uneventful. SF started out like virtually all the naive subjects we have run. On the first day, he simply tried to hold everything in a rehearsal buffer, and this strategy resulted in a perfectly average span of 7 digits. The next three days, SF tried another common strategy: Separate one or two groups of three digits each in the beginning of the list, concentrate on these sets first and then set them "aside" somewhere, and then hold the last part of the list in the rehearsal buffer; at recall, retrieve and recall the initial sets while simultaneously concentrating on the rehearsal buffer, and then recall the rehearsal buffer. (This strategy represents the first rudimentary use of a retrieval structure, which is the second component of the skill, to be described later.) This simple grouping strategy seemed to produce a slight improvement in performance (to 8 or 9 digits), but by Day 4, SF reported that he had reached his limit and no further improvements were possible.

And then, on the fifth day, SF's span suddenly jumped beyond 10 digits, and he began to report

the use of a mnemonic aid. From then on, SF's performance steadily increased, along with the reported use of his mnemonic system and accompanying retrieval structure.

It turned out that SF was a very good long-distance runner--a member of an NCAA championship cross-country junior-college team--and he was using his knowledge of running times as a mnemonic aid. For example, 3492 = "near world-record mile time". He initially coded only 1- and 2-mile times, but he gradually expanded his mnemonic codes to include 11 major categories from 1/2-mile to marathon. In addition, he added years (e.g., 1943 = "near the end of WW II"), and later he added ages for those digit groups that could not be coded as running times. For example, 896 can not be a time because the second digit is too big, so SF coded this digit group as "eighty-nine point six years old, very old man." Table 1 shows the major categories used by SF and the session number when they first appeared in the verbal protocols. By the end of 6 months--100 sessions--SF had essentially completed his mnemonic system and he was coding 95% of all digit sequences, of which the majority were running times (65%), a substantial minority were ages (25%), and the rest were either years or numerical patterns (5%). After 200 hours, SF coded virtually everything.

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Insert Table 1 about here
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Later, when we wanted to see if it was possible to train another subject to use SF's mnemonic system, we were able to enlist another exceptional runner, DD, who was a College Division III All-American cross-country runner. DD was able to learn SF's mnemonic system without any trouble, although the system he eventually developed is somewhat different due in part to the differences in the races he specializes in. DD also coded virtually everything after 200 hours of practice, and the relative proportions of running times, ages, years and numerical patterns were similar to SF's.

It should be emphasized that the semantic memories of our two subjects are very rich. That is, SF and DD do not simply code digit groups as a member of a major category; there are many

sub-categories within each major category. For example, there are dozens of types of mile times: near world-record, good work-out time for high school, training time for the marathon, etc. Table 2 is a listing of the 1-mile categories around 4:00 derived from DD's verbal protocol when he was recently asked to sort into categories a deck of 31 cards with running times ranging from 3:40 to 4:10. The left-hand column of Table 2 contains the categories derived from a different protocol taken from SF three years earlier, after SF had had about 3 months of practice on the digit-span task. In this early protocol, we asked SF to divide the running-time spectrum into categories, although we did not ask him to describe each category. We were simply interested in determining the size of SF's semantic network for running times. In that early protocol, SF reported 210 distinct running-time categories, including 81 1-mile categories. When this protocol was taken (after 3 months of practice), SF was coding mostly 1-mile and 2-mile times, which together comprised two thirds of the 210 categories reported by SF at that time.

Despite the differences in procedures, different amounts of practice, and important changes in the running world, it is interesting to examine the two sets of categories side by side. Although there is little direct correspondence of categories, there are some striking similarities. There are 10 or more distinct categories for each subject over this small range, many of which contain only a single (non-decimal) time. Note in DD's protocol that several times are associated with specific events or people. This table illustrates an important point about these mnemonic codes: they are semantically rich and distinctive.

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Insert Table 2 about here

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On the basis of SF's verbal protocols, we were able to figure out his coding rules, and eventually we were able to incorporate these rules into a computer simulation model that predicted how SF would code a string of digits, with 90% accuracy. We have also conducted many experiments to test our theory of SF's coding system.

The first two experiments we conducted (Days 42 and 47) were a direct test of SF's mnemonic system. We hypothesized that if SF were using a mnemonic system and we presented him with digit sequences that he could not code with his mnemonic system, then his performance would decline. We therefore presented SF with digit sequences that could not be coded as running times or easy numerical patterns. At that time, SF had not yet invented other categories for digit sequences that were non-times. As expected, SF's performance dropped about 20% from his normal average of 16 digits. In our second experiment, we presented SF with digit sequences that could all be coded as running times, and under these circumstances, SF's performance jumped by over 25%.

We have several other pieces of evidence that our.subjects are using long-term memory in the digit-span task. Perhaps the most straightforward evidence is that both our subjects can recall almost all the digit sequences that they have heard after an hour's session, although they can't remember the order. Both our subjects, when asked to recall everything from a session, systematically recall 3- and 4-digit sequences category by category, starting with the shortest times (1/4-mile times in DD's system, and 1/2-mile times in SF's system) and they work their way through to the longest times (marathon), followed by ages, years and patterns. Further, within each category, they generally also start with the shortest times and work their way through to the longest times. We believe that our subjects are using a simple generate-and-test strategy to search their semantic memory categories for recently presented items. To give a concrete example of the generate-and-test strategy in another domain, suppose you asked subjects to name all the states in the union that begin with the letter "m". One common strategy is to generate initial consonant-vowel sounds beginning with /m/, systematically working through all the vowel sounds, and see if any states come to mind. By "come to mind" we mean that a retrieval cue is sufficiently similar to a node in long-term memory to cause its activation. In the subsequent recall task of our experiment, we believe that our subjects systematically think of running times within small ranges, such as those described in Table 2, and if any such traces have been generated recently, there is a high probability that they will be re-activated.

Figure 2 shows the average percentage of items recalled by each of our subjects as a function of practice. Although we did not think of running this experiment until several weeks of practice had elapsed, we suppose that our two subjects were like other naive subjects in the beginning, which is to say that virtually nothing is recalled from a digit-span task after an hour's session. With practice, however, subsequent recall gradually approached 90% over the 200-300 hour range we studied.

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Insert Figure 2 about here

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In another experiment (after about 4 months of practice), we tested SF's recognition memory for digit sequences because recognition memory is a much more sensitive measure of retention than recall. On that occasion, SF not only recognized perfectly 3- and 4-digit sequences from the same day, he also showed substantial recognition of sequences from the same week. In another experiment (after about 4 months of practice), after an hour's session we presented SF with 3- and 4-digit sequences, but with the last digit missing and he was asked to name the last digit. SF was able to recall the last digit 67% of the time after 4 months of practice; after 250 hours of practice, SF was virtually perfect at naming the last digit of a probe.

Finally, we ran an extended recall session after Day 125 (Williams, 1976). At that time, SF was normally recalling about 80% of digit sequences from the session, and he generally took about 5 minutes to do it. We asked SF to try harder, and keep trying until he could recall all the digit sequences from the session. After about an hour of extended recall, SF had recalled all but one 4-digit sequence from the session. Every time we have asked for extended recall since then, SF has shown virtually perfect recall. We recently ran DD on extended recall after Session 286 and he too had virtually perfect recall (97%).

Up to this point it seems clear that our subjects are making extensive use of semantic memory. We next address a question of theoretical importance concerning the role of short-term memory in this task.

2.2.2. Short-Term Memory

How much information is being processed in short-term memory? Has the extensive practice produced an increase in the capacity of short-term memory? In one experiment, we attempted to determine how much information is in short-term memory by asking SF. In this experiment, we interrupted SF at some random point during a trial while he was being presented with digits, and we asked for an immediate verbal protocol. We wanted to know what SF's running short-term memory load was and how far behind the spoken sequence he lagged. That is, how many uncoded digits and how many coded groups are kept in short-term memory? From SF's verbal reports, we found that he was actively coding the previous group of 3 or 4 digits while the digits for the current group were still coming in, a lag of about 4 to 7 sec in time. DD's verbal reports show a similar pattern, although he reports more information about numerical patterns within groups and semantic patterns between groups. For example, typical relations noticed by DD, given the sequence 415527 are "a four-fifteen mile time with a repeating digit for the decimal; the time was run by a twenty-seven year-old man." The interesting fact from both subjects' protocols is that very little except the most recent few seconds are in short-term memory at any moment in time. We conclude that the contents of short-term memory include: (1) the most recent one, two or three uncoded digits, (2) the previous group of three or four digits, and (3) all the semantic information associated with the mnemonic coding of the previous group.

In a series of rehearsal-suppression experiments, we wanted to see how much of the digit series was retained if the rehearsal interval between presentation and recall were disrupted. In one experiment, immediately after the list was presented, SF recited the alphabet as quickly as possible for 20 sec before recall. This procedure resulted in the loss of only the rehearsal buffer at the end--the last group of 3-5 digits at the end of the list. In two other experiments, we suppressed visual rehearsal by having SF either copy or rotate and copy geometric shapes for 20 sec in between presentation and recall. This procedure has been shown by Charness (1976) to interfere with short-term visual retention. However, in the digit span task, this visual suppression procedure had no effect

on performance.

Two further experiments were designed to interfere with short-term memory processes *during* the presentation of digits. In one experiment, we introduced a concurrent chanting task ("Hya-Hya") that has been used by Baddeley and his associates to suppress short-term memory (Baddeley & Hitch, 1974). In this task, SF said "Hya" after each presented digit. This procedure produced no decrement whatsoever, and SF reported that he organized the chanting in a different phenomenal (spatial) location than his perception and coding of digits. In the second experiment, we produced a very substantial amount of interference with a concurrent shadowing task. We presented SF with a random letter of the alphabet between each digit-group boundary (every third or fourth digit), and his task was to say the presented letter as soon as he heard it. One experimenter read digits to SF at the rate of 1 digit per sec, and the other experimenter read a letter at the end of each group. Unlike the concurrent chanting task, this procedure produced a 35% drop in performance, even though there was only *1/3 to 1/4 as much verbalization required* by the subject. It appears that the concurrent chanting task does not interfere with the phonemic short-term memory buffer, as Baddeley (1981) has also recently concluded. However, we believe that the shadowing task interferes with SF's normal strategy of lagging behind the input of digits and using the phonemic short-term memory buffer as a temporary storage for the incoming group while processing semantically the immediately preceding group.

Finally, there is other evidence to suggest that short-term memory capacity did not increase with practice. (1) SF's and DD's mnemonically coded groups were virtually always 3 and 4 digits. (2) Their rehearsal group virtually never exceeded 6 digits. (3) In their hierarchical organization of digit groups (to be described later), SF and DD never grouped together more than 3 or 4 digit groups. (4) There was no increase in SF's or DD's consonant letter span with practice on digits. (5) Without a single exception in the literature, expert mental calculators and other memory experts have digit groups of 3-5 digits (Hunter, 1962; Mitchell, 1907; Müller, 1911).

These many converging lines of evidence led Chase and Ericsson (1981) to conclude that the reliable capacity of short-term memory is 3 or 4 units, independent of practice. The usual measure of short-term memory, the span, is the length of list that can be reported 50% of the time. However, the optimum group size for digits is 3 or 4 digits (Wickelgren, 1964), the *running* memory span is only about 3 digits, and long-term memory groups are also 3 or 4 items (Broadbent, 1975). Thus, the *reliable* capacity of short-term memory--the amount of material available almost all the time-- is closer to 3 or 4 symbols. In speeded skills, 3 or 4 symbols is a more realistic estimate of short-term memory capacity.

In the digit-span task, the evidence seems to uniformly suggest that only a very small portion of the list of digits is in short-term memory at any point in time. During presentation, only a few seconds worth of material is in short-term memory, and after presentation, only the last group of 3-6 digits is rehearsed. Almost everything seems to be mnemonically coded in long-term memory. This leads to our next problem: If these digit groups are in long-term memory, how do subjects retrieve them?

2.2.3. The Retrieval System

The simple model of retrieval in skilled memory proposed by Chase and Simon (1973a,b) is clearly inadequate to explain digit-span performance by our experts. They proposed that retrieval cues for chess patterns are stored in short-term memory and then used at recall to retrieve items from long-term memory. First, the rehearsal suppression experiments showed that very little coded information is retained in short-term memory. Second, both SF and DD recall too much (22 digit groups for SF and 19 digit groups for DD). Third, we ran a subject who used this simple strategy, and her digit span reached an asymptote of about 18 digits, or 4 mnemonically coded groups of digits. This subject developed a mnemonic system based on days, dates and times of day, e.g. 9365342 = "September third, 1965, at 3:42 P.M." This subject never developed a retrieval system, and she tried to hold the retrieval cues for these mnemonic codes in short- term memory. Her performance improved about as rapidly as SF's and DD's in the beginning, but she could never improve her performance above 4 mnemonic groups and she eventually quit the experiment from loss of

motivation after about 100 hours.

We have several reasons for proposing that our subjects developed what we have termed a retrieval structure. A retrieval structure is a long-term memory structure for indexing material in long-term memory. It can be used to store order information, but is more versatile because it can allow direct retrieval of any identifiable location. A good example of a retrieval structure is the mnemonic system known as the Method of Loci because it provides a mechanism for retrieving a series of concrete items associated with identifiable locations via interactive images. We suggest that our subjects have developed a retrieval structure, analogous in some respects to the Method of Loci, for retrieving mnemonically coded digit groups in the correct order.

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Insert Figure 3 about here

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The verbal protocols are very revealing about the retrieval structures. Before every trial, SF and DD both explicitly decide how they are going to group the digits. Figure 3 illustrates the development of SF's retrieval structure, as revealed in his verbal protocols. SF started out by relying only on the short-term phonemic buffer (R) as his retrieval mechanism until he hit on the idea of setting aside the initial groups of digits and holding only the last few digits in the rehearsal buffer. This strategy is fairly common among subjects, however, and it is not unique to our skilled subjects. What makes the retrieval structure so powerful is that SF was able to store his mnemonically coded digit groups in these locations. Without the mnemonic, it is not clear how subjects would be able to associate very many distinctive items with the different locations. Even so, SF experienced a great deal of difficulty keeping the order straight for more than three or four groups of digits.

After about a month of practice, SF introduced a very important innovation in his retrieval structure: hierarchical organization. He began to separate groups of four digits followed by groups of three digits. We have termed these clusters of groups "supergroups". Finally, when these supergroups became too large (more than 4 or 5 groups), SF introduced another level in his hierarchy

(Day 109), and his performance improved continuously thereafter. DD's hierarchical organization is very similar to SF's, and Figure 4 illustrates our best guess as to SF's grouping structure for 80 digits, and DD's grouping structure for 69 digits. At their current levels of practice, SF and DD use at least a 3-level hierarchy: (1) Digits --> Groups, (2) Groups --> Supergroups, and (3) Supergroups --> Clusters of Supergroups.

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Insert Figure 4 about here

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In another study, run separately on SF and DD, after an hour's session we presented our subjects with 3- and 4-digit groups from the session and asked them to recall as much as they could about that group. Subjects invariably recalled the mnemonic code they used and they often recalled the location of the group within the supergroup. On those rare occasions when they were able to recall a preceding or following group, this recall was always associated with some relation between the groups, such as two adjacent 1-mile times. With the exception of this type of episodic information, retrieval of these mnemonic codes seems to be achieved via these hierarchically organized retrieval structures rather than through direct associations between digit groups.

Another interesting aspect of our subjects is that they generally spend between 30 sec and 2 minutes rehearsing the list before they recall it, and their rehearsal pattern is revealing about the underlying retrieval structure. According to their verbal reports, both subjects rehearse the digit sequence in reverse, supergroup by supergroup, except the first supergroup. That is, both subjects rehearse the last supergroup, then the next-to-last supergroup, and so on, until they come to the first supergroup. Instead of rehearsing this initial supergroup, the subjects then go directly to the beginning of the list and start their recall. Within supergroups, SF generally rehearses in forward order and DD rehearses in reverse order. The interesting thing about these rehearsal patterns is that rehearsal is organized in supergroups.

Besides the verbal protocols, there is a great deal of additional evidence that our subjects use

retrieval structures. The best evidence comes from the speech patterns during recall. In the literature, pauses, intonation and stress patterns are well-known indicators of linguistic structure (Halliday, 1967; Pike, 1945). The speech patterns of SF and DD typically follow the same pattern. Digit groups are recalled rapidly at a normal rate of speech (approximately 3 digits per sec) with pauses between groups (about 2 sec between groups, on average, with longer pauses when subjects experience difficulty remembering). At the end of a supergroup, however, there is falling intonation, generally followed by a longer pause.

In another study, we conducted a memory search experiment with SF after about a hundred days of practice. We presented SF with a list of digits but, instead of asking for recall of the sequence, we presented SF with a group of digits from the list and asked him to name the preceding or following group of digits. It took SF more than twice as long to name the group preceding or following the probe if he had to cross a hierarchical boundary (10.1 vs 4.4 sec).

Up to this point, we have described the two most important mechanisms underlying our subjects' memory performance: The mnemonic system and the retrieval structure. However, these mechanisms are still not sufficient to fully explain the performance of our subjects. These systems were essentially completed within the first 100 hours of practice for both subjects. Yet the performance of both subjects showed continuous improvements through 250 hours of practice, and there is no sign of a limit. There must be another mechanism.

2.2.4. Encoding and Retrieval Speed

This aspect of memory skill has been the most illusive mechanism to track down. For one thing, our subjects' verbal reports are of little use in analyzing changes in the speed of mental operations. For another, we have not been able to obtain a great amount of data supporting our theory of speedup. Nevertheless, we believe that the little evidence we have suggests that speedup is an important mechanism in skill acquisition in the memory span task.

We have recorded latency data on both SF and DD in a self-paced presentation task several

times over the past three years. In this task, we presented subjects with one digit at a time on a computer-controlled video display, the subject controlled the rate at which he received digits by pressing a button each time he wanted a digit, and we measured the time between button pushes. We also systematically manipulated the size of the list.

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Insert Figure 5 about here
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Figure 5 shows these latency data for both subjects as a function of the size of the list and practice. As one might expect, pauses tend to occur between groups, so we have displayed only the time between groups in Figure 5. For both subjects, pause time increases with the size of the list. This result has been known for many years (Woodworth, 1938, p. 21), namely, that there is more learning overhead for larger lists.

The practice data are not as clear-cut for DD as for SF. Over a 2-year period, SF's coding time has shown a very substantial decrease, and the decrease interacted with the size of the list such that there are bigger practice effects for larger lists. In SF's case, the practice effect is so pronounced that there seems to be very little learning overhead for the larger lists after a couple of hundred hours of practice.

In another experiment, we have several direct comparisons between our subjects and other memory experts in the literature on the speed to encode a 50-digit matrix (from Luria, 1968). Subjects in this task are shown a 50-digit matrix of 13 rows and 4 columns, and timed while they study it. Subjects are then timed while they recall the matrix, and then they are timed while they recall various sub-parts of the matrix (rows, columns, diagonals, and so on). These data are shown in Table 3 for DD, two trials for SF spaced a year apart, for two well-known mnemonists in the literature (Hunt & Love, 1972; Luria, 1968), for our mental calculation expert AB, and for four unskilled subjects.

A close examination of Table 3 reveals several interesting results. First, there is an enormous difference between memory experts and unskilled subjects in the time needed to memorize the list.

Second, there is a large practice effect on learning time for SF. After a year's practice, SF was substantially faster than the other subjects on this task. Finally, there was very little difference in *retrieval* times among any of the subjects. This last result is unexpected, but it is interesting because it suggests that retrieval time depends upon how well learned the matrix is rather than on memory skill per se. That is, unskilled subjects can achieve almost as rapid retrieval as memory experts, provided that they take the time to learn the digit matrix as well as the memory experts. In speeded tasks, of course, we would expect a deterioration in retrieval speed for the unskilled subjects because learning time would be severly limited.

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Insert Table 3 about here

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It is possible to compare SF's learning time on the 50-digit matrix with Rückle's data (Figure 6), reported by Müller (1911). As far as we know, Rückle's data represent the fastest learning times ever reported in the literature for digits (Woodworth, 1938, p.21), and SF's times are comparable after 2 years of practice. The data of Figure 6 are only for visually presented lists; Rückle's auditory digit span was only about 18 digits.

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Insert Figure 6 about here

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We mention one final experiment on encoding times. After about 50 hours of practice, we presented SF with digits at a rapid rate (3 digits/ sec) and we found that SF could not code digits presented at this rate and his performance dropped back to 8 or 9 digits. However, after 250 hours of practice, SF and DD were both able to code digits at these fast rates. They were both able to code one or two groups of 3 digits each and hold about 5 digits in their rehearsal buffer, to achieve a span of about 11 digits.

This concludes our review of the major mechanisms underlying skilled performance in the memory span task. We next present our current ideas for a theory of skilled memory, along with some additional theoretical issues and more data of interest.

3. A Theory of Skilled Memory

We perceive the central issues of a theory of skilled memory to be the following. First, what is the structure of long-term memory? Second, what are the storage and retrieval mechanisms that operate on this semantic memory to produce skilled memory performance. Finally, what role do retrieval structures play in skilled memory performance, and in general, what is the role of working memory in skilled performance?

3.1. The Structure of Long-Term Memory

3.1.1. Semantic Memory

We assume that our subjects' knowledge of running times is stored as a hierarchical structure, which can be represented as a discrimination tree. In Figure 7, we illustrate that portion of DD's semantic network outlined earlier in Table 2. We assume that as digits are presented to DD, he searches his discrimination tree for these categories. When he searches to a terminal node, we assume that recognition has taken place and a link is established between the terminal node in the semantic network and the episodic trace of the current digit group in short-term memory.

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Insert Figure 7 about here
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There are several aspects of our subjects' behavior that are consistent with this assumed structure. First, it explains the systematic generate-and-test characteristic of our subjects' recall after the session. We assume that they simply search through this structure, activating each terminal node in turn, and from a terminal node they then activate any links between that terminal node and associated traces and report these traces.

Second, there is evidence in the verbal protocols that subjects search a hierarchical structure. When we stopped subjects in the middle of a trial and asked for the contents of short-term memory (reported earlier), our subjects reported that when they are being presented with digits, they first notice the major category before making any finer-grain categorizations. For example, given 357,

they first notice that it is a 1-mile time before they notice that it is near the 4-minute barrier. DD, in fact, explicitly reported that he waits until he hears the first two digits before he thinks about the category because one digit is too ambiguous. In our model of the semantic structure, two digits are sufficient to activate a non-terminal node in the tree whereas one digit is not. After hearing two digits, DD says that he then makes a category decision (age, mile-time, etc.) and then the third digit is used to find a more meaningful category if possible.

Finally, we report some latency data on SF that supports our hierarchical model. In this experiment, after a session SF was presented visually with a digit group with one digit missing, and the task was to name the missing digit. Figure 8 shows that both the mean latency and the variance decreased monotorically with the position of the missing digit in the probe from first to last position, corresponding in our model to depth in the hierarchy. Further, the mean latencies decreased over a fairly large range (approximately 8 sec to 1 sec); a mean latency of 8 sec indicates a considerable amount of memory search. SF's verbal protocols indicated that the earlier the missing digit is in the probe, the more extensive is his memory search. When the missing digit was in the third and fourth positions, SF often reported having direct access to the memory trace without any conscious awareness of search.

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Insert Figure 8 about here

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3.1.2. The Retrieval Structures

The second type of long-term memory structure that is relevant to skilled performance in the digit span task is the retrieval structure. We assume that SF's and DD's retrieval structures have the hierarchical forms portrayed in Figure 4, and that they can also be systematically searched. In the beginning, we assume that the nodes in this retrieval structure are minimally differentiated, but with practice, each node takes on a distinctive set of features. That is, we assume that it takes practice, *extensive practice*, to use this retrieval system, just like any mnemonic system, and that practice involves learning to generate a set of distinctive features to differentiate one location from another.

As with any mnemonic system, the more distinctive the better.

One important issue concerns how versatile are these retrieval locations: What exactly can be stored in these locations? We had assumed that these locations were specific to abstract numerical concepts -- running times, ages, years and patterns for our subjects -- because our subjects' letter span didn't improve along with their digit span, although we did not give our subjects much practice with letters. In another experiment, SF was able to store and recall perfectly a list of 14 names using his retrieval structure, so we do have some tentative evidence that these retrieval structures can store information other than digits. Storage locations in mnemonic systems have a similar limitation, but they seem more versatile. For example, the locations in the Method of Loci are specialized for concrete items for which a visual image can be generated. Rhymes are specialized for phonemically similar patterns.

As we will discuss later, we think of a retrieval structure as a featural description of a location that is generated during encoding of digit groups and these features are stored as part of the memory trace of a digit group. Then at recall, these features will serve as a mechanism for activating the trace, when the featural description is attended to. The idea of a retrieval structure as a set of features stored with the memory trace, we believe, explains a great deal about the types of confusion errors that we have observed (to be described later).

3.1.3. Context

Finally, there is a third type of long-term memory structure that is relevant to the digit span task: the context. We think that it is necessary, in any case, to suppose that attended information is associated with the current context -- the day, the trial number, the list length, the room and building and probably much more. Further, we think that attended information is automatically bound to the current context, unlike the retrieval structure, which requires control processes to bind information. We think that it is necessary to postulate the existence of current context because otherwise, how is information not in short-term memory normally retrieved? That is, the every-day retrieval structure or

working memory that people use all the time to retrieve recent facts not in short-term memory, but relevant to the ongoing task is the context. We don't have any concrete ideas about the form of the context. but it is probably not unreasonable to suppose that there is some type of hierarchical knowledge structure, analogous to a script, to which the current events are bound in some stereotypic fashion. In any case, we assume that in the digit span task, memory traces are associated with the current context.

3.2. Short-Term Memory and Attention

We simply assume that short-term memory is the set of knowledge structures that are currently active. Thus, short-term memory can contain graphic, phonemic and semantic features. The rehearsal buffer, we assume, is a *control structure*, or *retrieval structure* if you will, for storing the order of a set of phonemic or articulatory features. We assume for some basic unspecified reason, there is a limit to the number of knowledge structures that can be active at any moment in time.

Attention refers to a property of the information processing system which limits processing. The contents of attention refer to that subset of information in short-term memory that is attended to, and by "attended to", we mean that this information serves as input to a process that requires attention. There is a class of processes that interfere with each other, that compete with each other for sensory input channels, for short-term memory space, they slow each other down, and so on. These processes are said to be attention-demanding or controlled. Without getting involved in an elaborate discussion of the nature of attention, we will simply state that short-term memory places a limit on the number of knowledge structures that can be held simultaneously as input to a control process. As we discussed earlier, this limit seems to be about 3 or 4 symbols for the chunking process. We will equate our binding operation in long-term memory with attention. Our short-term memory and attention assumptions are of little consequence for the digit-span task, except that only one or two digit groups and their associated semantic information are in short-term memory at any point in time. The interesting assumptions concern storage and retrieval operations.

3.3. Memory Operations

3.3.1. Storage

Our storage assumption is very simple: memory traces attended to at the same time as an active long-term memory node are bound to that node, provided that they fit the range of that node. For example, in Figure 6, DD's node for a GOOD COLLEGE MILE TIME will fit any time from 4:03 to 4:12; this node is not a good mnemonic for any sequence of digits, but only for a sequence of digits in the range specified.

We adopt a featural representation of binding in which the memory trace and the semantic features activated from long-term memory are chunked together by virtue of being attended together. In the digit span task, we assume that a digit group is bound to three long-term knowledge structures: the mnemonic association, the *retrieval structure, and the current context*. To take a concrete example, what happens when DD hears the digit string 4054? First, as the digit string is being perceived, he actively attends to the magnitude of the digits in order to classify it in his mnemonic system. As he perceives the first two digits, that is sufficient to activate two features in semantic memory corresponding to RUNNING TIME and 1-MILE. When he perceives the third digit, that is sufficient to activate the semantic feature of GOOD COLLEGE TIME, and when he hears the fourth digit, he notices that it is the same as the first digit, which activates a feature corresponding to SAME AS FIRST DIGIT. (We will describe how our subjects parse decimals more fully later when we discuss discrimination.)

This set of features is simultaneously attended to along with the trace of 4054, and a new memory chunk is formed. The current context and the location in the retrieval structure are also bound to the memory trace. The subject, as he is decoding the mnemonic code, also simultaneously thinks of the location within the retrieval structure and the current context, and featural descriptions of these long-term memory structures are activated and attended to simultaneously along with the trace and its mnemonic code. For example, suppose that DD notices that the previous group was also a 1-mile time, that it was faster, *that these represent First and Second place, respectively*, in

some imaginary race and further that he had a similar time, 406.2, on the previous trial (a typical report). This information is also included as part of the context. Figure 9 depicts the final memory trace for 4054.

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Insert Figure 9 about here

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We believe that this representation is consistent with a large number of observations. The additional links in Figure 8 are included to illustrate the variety of associations that we have observed. The link between the location and the semantic code reflects the fact that subjects very often know any of several semantic features without knowing the actual digits. In fact, subjects' verbal protocols indicate that the semantic code is invariably retrieved first, suggesting that the major link between the location and the trace is through the semantic code. However, the direct link between location and trace is necessary because subjects are able to recall digit groups without semantic codes.

The links between context and location and between context and the semantic code are there because the local context can be used to disambiguate either or both. The dotted lines indicate that the context contains information about other digit groups; the existence of these links is clearly seen in the clustering that occurs in the after-session recall. The direct link between the context and the trace is there because people can still recall small recently-heard groups of digits even though they are not in short-term memory, provided that there haven't been too many such sequences. In our theory, context is virtually useless because it is not unique: if several digit sequences have been linked to the same context, then there are too many links to achieve activation.

Finally, one might ask why it is necessary to assume a trace at all. Why isn't memory retrieval a reconstructive process in which the set of features represents a sufficient code to reconstruct the event (Neisser, 1967)? The answer is that the semantic code is <u>not</u> sufficient to uniquely specify the event. In our example, GOOD COLLEGE TIME only specifies a range; in DD's semantic network, there are a hundred possible times (including decimal times) that could fit this category. What the

semantic code does is narrow down the search in long-term memory for the memory trace. A good mnemonic should narrow the search down to a single trace. But there still must be a trace.

Our theory is consistent with two related observations in the digit-span task concerning the retrieval structure: the limited size of supergroups and the hierarchical organization of the retrieval structure. Why should this be true? After all, there doesn't seem to be any such constraints with other mnemonic systems, such as the Method of Loci. We speculate that with the Method of Loci and other mnemonic systems, the locations are so rich and distinctive that subjects have no trouble differentiating them. However, in the digit-span task, the subjects face the problem of building retrieval structures from nothing but position information. How is the subject to do this? We suppose that the subjects build supergroups by chunking them. That is, at the end of a supergroup, the subject must, according to our encoding assumption, attend to all groups simultaneously in conjunction with the current context. In fact, subjects' introspections suggest that they are able to attend to only a few semantic features while grouping. Thus, according to our theory, the short-term capacity places a limit on the size of supergroups, and the hierarchical structure occurs because subjects have only enough capacity to group together a few abstract features representing groups, rather than the groups themselves.

Another interesting property of the memory representation is redundancy. It is very common in our subjects' retrospective reports that they notice such things as repeating semantic codes (e.g., two 1-mile times in a row) and many other kinds of relations. These redundant relations are very important to our subjects because they help to disambiguate the memory code and they aid in error recovery. It is very common for our subjects to retrieve only a very few features associated with a trace, and, with a combination of inference and further search, eventually recover an error or retrieve a missing trace. Also, our subjects are good at judging certainty of their answers, and they can virtually always indicate when a digit group is right or wrong. The redundancy of the memory trace is a possible mechanism for this judged certainty.

Before describing our retrieval assumptions, we should point out that our theory has focused on meaningful associations as the major mechanisms for building long-term memory structures, and we have said nothing about trace strength. This is in contrast to most memory theories, which focus on repetition as the major mechanism, and dwell time in short-term memory is the major determiner of strength (e.g., Anderson & Bower, 1974; Atkinson & Shiffrin, 1968; Raaijmakers & Shiffrin, 1981). We believe that both mechanisms operate, that attention time and number of redundant associations jointly determine the strength of meaningful associations, and this distinction between attention and meaningful associations vs short-term memory occupancy and rote repetition underlies the empirical distinction between elaborative and maintenance rehearsal (Bjork, 1975; Craik & Watkins, 1973). We believe that meaningful associations are much more powerful, useful and pervasive, and that rote rehearsal is the default mechanism that people use when they can't think of any meaningful associations.

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Insert Figure 10 about here
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3.3.2. Retrieval

The process of retrieval during a trial, we assume, involves attending to a set of features in short-term memory, and this attention process will cause the activation of memory traces in long-term memory which contain the set of features. After a trial, with no information in short-term memory except an index to the current context, recall begins by activating the current context along with the first location of the retrieval structure. This should result in activation of the location information contained in the memory trace. From there, we assume that activation spreads jointly to the trace and to the semantic code, and spreading activation from the semantic code to the trace should normally be sufficient to activate the trace. In the case of recall after the session, retrieval is achieved by activating links between semantic memory and the trace. However, it is commonly reported by both SF and DD that during a trial when they have trouble remembering a digit group, they use the alternate, time consuming strategy of searching for it in semantic memory. When they don't know the mnemonic category, it sometimes takes SF and DD several minutes to search the semantic network

before they retrieve an item. Figure 10 illustrates the various retrieval routes to the memory trace.

It is interesting to compare the retrieval times for semantic memory and working memory (i.e., the retrieval structure). In four memory search experiments (after about 100 hours of practice), we timed SF as he responded to a probe after being presented with a sequence of 30 digits. Two of the experiments involved accessing information via semantic memory: (1) Name the last digit of the probe, and (2) Point to the location of the probe. In the first experiment, we assume that the first digits of the probe lead SF directly to the appropriate node in semantic memory, and SF uses the features of this node to activate semantic information in the memory trace. In the second experiment, SF is given the probe and he must point to the location of the probe in a graphic representation of the retrieval structure. In this case, we assume that the probe activates the memory trace, which in turn activates the features corresponding to its location in the retrieval structure. In both cases, there is only a single, direct link to activate, and the average latency was 1.6 sec (S.D. = .49 Sec).

The other two experiments involved searching the retrieval structure for the trace: (1) Name the digit group pointed to in a graphic representation of the retrieval structure, and (2) Name the group preceding or following the probe. In the first case, search begins with the retrieval structure, as in a normal recall trial, and in the second case, the probe is first used to derive its location information, and from there, the retrieval structure is entered. Unlike the previous two tasks, retrieval is achieved via the retrieval structure. In both these cases, search time was much slower (average = 6.4 sec, S.D. = 2.9 sec). We interpret these results to mean that direct access in semantic memory is automatic and fast; access in working memory is controlled and relatively slow (Schneider & Shiffrin, 1977). As a corollary, we assume that the bottleneck in skilled performance is access to working memory, and that practice has its greatest effect on the speed of storage and retrieval operations in working memory.

3.3.3. Differentiation

Differentiation refers to processes that produce unique memory traces. We describe two such processes that our subjects use: (1) updating semantic codes, and (2) coding the decimal place.

According to our theory, mnemonics and meaningful associations derive their power from their ability to narrow the search in long-term memory to a unique memory trace. We have already discussed the role of redundancy in search. We have evidence from our subjects' protocols that another mechanism is operating, a mechanism we will call *updating*. The issue concerns what happens when the subject is presented with more than one digit group within the same mnemonic category? In the example presented earlier, what happens when the subject hears 4054 after hearing 4062 on a previous trial, since they both belong to the same semantic category? If they are not differentiated, then the semantic category will no longer serve as a unique cue to the memory trace. According to our theory, when the subject perceives the current digit group and activates the semantic features for the mnemonic category, this automatically results in the activation of any previous memory traces from the same category, within the same context. Thus, in our example, upon categorizing 4054, 4062 (from the same category) is automatically reactivated, and this information is incorporated in the new memory trace. It is reasonable to suppose that a new hierarchical memory trace is formed from the combined memory traces, including any comparative information between the two traces, such as which is greater in magnitude.

We have some evidence that updating is, in fact, occurring with our subjects. First, updated items are invariably recalled together in the after-session recall. The average pause times between these items clustered in the output, for a sample of updated items taken from DD's protocols, was 1.6 sec (S.D. = .92 sec), compared to 3.2 sec (S.D. = 3.32 sec) for pause times between nearby items. Second, on several sessions, we asked SF in his verbal reports after each trial to tell us when a digit group had reminded him of an earlier group. Out of a sample of 276 digit groups from two sessions, SF noticed similarities in 47 groups, approximately 17%. Our other subject, DD, reports slightly fewer such instances of updating (about 13%). In one experiment, after a regular practice session of 60

digit groups presented in six sequences, we presented DD with probes with varying degrees of similarity to the groups from the session. We presented these probes at the usual 1-sec per digit rate and we instructed DD to code them as he would in a normal session, but to indicate immediately when a probe reminded him of an earlier sequence. In this experiment, DD only recognized digit sequences in which the first three digits matched a previous group, and recognition occurred within a second after hearing the third digit. Thus, both subjects appear to be updating their memory traces. Finally, the speed of the process -- somewhere between 1-sec or less to as much as 2-sec -- is suggestive of the fast-access automatic retrieval from semantic memory that we described earlier.

Both of our subjects report that they code decimal digits in terms of numerical patterns, although DD's system is much more elaborate than SF's. Figure 11, derived from SF's verbal protocols illustrates his coding system for decimals, which is basically designed around reference points. This simple system contains a total of only 9 parsing rules, or 9 features, that SF uses to code the decimal.

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Insert Figure 11 about here
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In contrast, DD's system is much more complicated. In one experiment, we asked DD to sort 181 running times (printed on cards) in the range 3400 to 4100 into equivalent piles. Within semantic categories, we counted 29 rules, all based on numerical relations, that DD used to code the decimal. Only four of these rules were similar to SF's in that they assigned a feature to the decimal, based only on the magnitude of the decimal. These rules were, using DD's terminology: (1) 0 = "flat", (2) 5 = "half", (3) 8 or 9 = "almost" and (4) 1 or 2 = "just above". The rest of the rules all involved numerical relations between the last digit and the preceding digits. These include such things as the last digit is the same as one of the preceding digits, the last digit is above the preceding digit by 1, 2, or 3, the digits are all odd or all even, the last digit is some numerical combination of some of the previous digits, and so on. Further, there is a rule hierarchy because the rules overlap. The point is that DD's system is a very complex but rule-governed system for coding the last digit in terms of

numerical patterns. The system is designed to discover a feature that can be used to uniquely code the decimal point relative to the semantically coded part of the trace.

Both SF's and DD's digit-coding systems seem to work extremely well. From an analysis of the errors, we found that the chance of making an error on the decimal, given that the semantic part of the trace is reported correctly, was less that 1% for both subjects. This error rate is quite low compared to the unconditional error rate per digit group of about 4%.

These two processes described in this section, we speculate, are instances of more general processes for differentiating semantic codes. Updating probably occurs all the time during normal cognitive processing; whenever more than one instance of an abstract category is noticed, it is important to keep them separate. The digit coding system, on the other hand, is probably an instance of the more general process of generating elaborated, redundant memory codes in order to facilitate retrieval and disambiguation of memory traces.

3.4. Interference

So far, we have said little about mechanisms of forgetting. However, we have some data on interference effects, most of which are describable within the theoretical framework we have outlined here.

Perhaps the most interesting data we have concern the buildup of proactive interference within a session. Figure 12 shows, for each subject over the last 100 sessions, the probability of recalling a sequence correctly as a function of the trial number within the session. Since we are using the up-and-down method, the average percent correct is 50%. For both subjects, there is a substantial increase in the error rate as the session progresses. Further, for both subjects there is also a substantial increase in the rehearsal interval as the session progresses. Figure 13 shows the average latency to begin recall as a function of trial number (for correct trials only, although the data are similar but slightly longer for incorrect trials).

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Insert Figures 12 and 13 about here

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There is an important theoretical issue here. Is this forgetting due to a loss of order information, or are the semantic codes being weakened? In our theory, as memory fills up with traces, is there a loss of differentiation because they can't be retrieved due to confusions among the similar locations in the retrieval structures, or are the semantic connections being lost? According to the Encoding Specificity Theory (Tulving, 1979), long-term memory traces are not lost; what is forgotten are the appropriate retrieval cues.

We have analyzed some data bearing on this issue. First, we analyzed 275 errors over an 86-day period for DD and 213 errors over a 78-day period for SF. As one might expect, there are many types of errors, almost all of which are at the group level: failure to recall a group, transposition of groups, intrusion of similar groups from earlier trials, and so on. In Table 4, we show a breakdown of errors into order errors and item errors. Item errors are more common than order errors, and the most frequent type of item error is reporting a digit group in the appropriate semantic category, but failing to get the digits exactly right. The most common type of order error is transposing two digit groups, usually from the same location between two supergroups. Thus, there are clearly some order errors, but there are more (partial) retrieval failures.

. . . .

Insert Table 4 about here

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The question still remains: what percentage of retrieval failures are caused by a loss of the connection between the location in the retrieval structure and the semantic code? Figure 14 presents some data bearing on this issue. These data show 10 days' worth of data for both subjects on the after-session recall task as a function of trial number. It is interesting to compare this figure with Figures 11 and 12: the after-session recall of digit groups is best for those digit groups showing the poorest recall within the session. These data clearly suggest that the buildup of proactive

interference over trials is due to a loss of connections between the location in the retrieval structure and the memory trace, because the memory trace is clearly accessible through the semantic code.

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Insert Figure 14 about here

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Another interesting result in Figure 13 is that there is a significant loss on the early trials; there does appear to be a weakening of the memory trace in semantic memory. According to the Encoding Specifity Principle, the difference between good and poor mnemonic codes should disappear with a recognition test because the after-session recall task is really a generate-and-test recognition procedure. These results suggest that some amount of forgetting has occurred for memory traces from the early part of a session, contrary to predictions from the Encoding Specificity Hypothesis. It could still be argued, however, that the after-session recall is not really a recognition procedure, and that much better performance was obtained with our recognition experiment (reported earlier). The alternative interpretation is that forgetting involves weakening of the connection between the semantic features and the memory trace.

Finally, we report an interference experiment designed to see how fragile is the retrieval structure. Is there a single schematic retrieval structure that is used over and over again, or are there multiple retrieval structures, one for each trial? We tested this possibility by giving DD two trials in a row and then we asked for recall of both lists; DD first recalled the most recent list, and then he recalled the previous list. In this procedure, DD was presented with the first list, and then given a normal amount of time to rehearse the list. However, instead of then asking for recall of that list, a second list was then presented to DD, followed by rehearsal of the second list and then recall. Only when the second list had been recalled did DD attempt to recall the first list. In an hours' session (on Day 195), we gave DD three pairs of lists of length 36 digits each. Although DD was unable to achieve perfect recall of two lists in a row, on two of the three trials, he missed perfect recall by only a single error. On the third attempt, he missed about 30% of the previous list. In short, DD is able to differentiate trials well enough that we reject the idea of a schematic retrieval structure.

We think the representation we have proposed in Figure 8 is compatible with all the empirical results. It accounts for the present results by assuming that the context can be used to differentiate retrieval locations from previous trials. At the same time, it accounts for the confusion errors observed between different retrieval locations by assuming a partial loss of location features in the memory trace. Intrusion errors from previous trials, according to the theory, are caused by a loss of context features in the memory trace, and semantic errors are caused by loss of connections between location features and semantic features in the trace.

3.5. Working Memory

In this section, we want to expand on what we think is an important implication of our work for a theory of skilled memory, and that is the concept of working memory. Working memory has traditionally been thought of as that part of the memory system where active information-processing takes place (Baddeley, 1976; Klatzky, 1980). Working memory is not exactly synonymous with short-term memory because short-term memory is usually taken to mean a passive storage system for item information, whereas working memory also contains control processes because they also require memory capacity. Baddeley and Hitch (1974) and Baddeley (1981) include the articulatory loop, the "visuo-spatial scratch pad" and a central executive as part of the structure of working memory.

The concept of working memory alone is not adequate to explain the performance of our skilled subjects in the digit-span task, or the skilled memory effect in general. Our research suggests that experts make associations with information in semantic memory, and they don't have to keep the information active during the retention interval; they can rely on retrieval mechanisms for reactivating information at recall. In the digit-span task, our subjects developed an elaborate retrieval structure for storing digit sequences. In the chess research, the reason the Chase and Simon (1973a, b) model underestimated the recall of Masters was because it assumed that information was retained in short-term memory.

We want to argue that the idea of working memory should be reconceptualized to include these

retrieval mechanisms that provide direct access to recent memory traces not in active memory. Perhaps this is a semantic distinction, and perhaps another term, such as *intermediate-term memory* (Hunt, 1971), should be used to refer to temporary knowledge structures relevant to the ongoing task. Nevertheless, these retrieval structures have the properties associated with working memory. The important properties of the short-term memory (STM) component of working memory are direct access and fast access to knowledge structures for input into processes. Retrieval structures provide direct access to knowledge structures, and they provide relatively fast access (say, within the range of 1-5 sec), thus avoiding the difficulties normally associated with long-term memory retrieval, namely search takes a lot of time and it causes interference by activating competing knowledge structures. Perhaps we should call these retrieval structures the intermediate-term memory (ITM) component of working memory.

An important point we want to make about skilled memory is that the size of the ITM component of working memory expands with skill acquisition, and the retrieval speed increases. We want to speculate that at high levels of skill, retrieval speed from ITM approaches that of STM, which is less than a second. Thus, the ITM can serve as a useful part of working memory, greatly expanding the available knowledge states as inputs to mental operations. We think this is one reason why performance of skilled experts in many domains seems vastly superior to novice performance.

This reconception of working memory is helpful in interpreting the literature in other domains besides skilled performance. For example, Shiffrin (1976) has argued that short-term memory does not have enough capacity to sustain performance in many tasks, and that context-tagged information in long-term memory is used to perform complex tasks. In other words, context can also serve as a retrieval structure for knowledge in some ongoing task, and hence can also serve as an important component of working memory.

One reason that Baddeley (1976, 1981) has argued for an expansion of the concept of working memory is because complex tasks such as reasoning, comprehension, mental calculation and

learning can proceed with very little decrement when subjects have to maintain a near-span digit load simultaneously in STM (Baddeley & Hitch, 1974). Kintsch (1981) has recently argued that the current concepts of STM and working memory are not adequate to account either for people's ability to retain and use the meaning of text during reading, or for their ability to retrieve more detailed propositional memory from reading text.

In a recent article, Daneman and Carpenter (1980) showed that a domain-specific measure of working memory capacity is a far better predictor of reading ability than the traditional short-term memory span. In this measure, subjects were required to read a series of sentences and then recall the last word of each sentence in order. Correlations between this measure of working memory and measures of reading comprehension were typically in the range of .7 to .9, whereas word span correlated only about .35 with measures of reading comprehension. Daneman and Carpenter argued that the reading processes of good readers are faster, more efficient, and they take up less capacity in working memory, thus releasing more storage capacity for knowledge structures in working memory, hence their higher sentence memory span. Good readers achieve better comprehension, according to Daneman and Carpenter, because they have more facts in working memory at any moment in time for their comprehension processes to work on.

Although we agree in principle with the idea that skill development is associated with automated processing, our theory of skilled memory requires a different interpretation of their result. The working memory of good readers is expanded, according to our theory, because they have developed better structures for organizing and retrieving information of various types relevant to the comprehension process from semantic memory during the reading process. Their larger sentence memory span, we argue, is the result of utilizing these structures for storing sentences -- or some deep-structure representations of the sentences -- in long-term memory. Nevertheless, we agree with the important point made by their experiment, namely that skill in some domain is associated with an expanded working memory.

We want to make one more point about encoding and working memory. How well an item is retrieved depends upon how it is coded for later use. This idea has been in the literature for some time as the encoding-retrieval interaction principle derived from the levels-of-processing literature (Tulving, 1979), and the constructability principle in the information-processing literature (Norman & Bobrow, 1979). The idea is that a good encoding anticipates how it will be retrieved because it builds into the representation, the retrieval cues that will arise at recall. In other words, skilled individuals have learned how to code information in a useful way so that when it is needed in some context, the retrieval cues will be the appropriate ones to achieve recall. It is typical of novices that they don't know when a fact is relevant, and they often fail to retrieve knowledge in their long-term memory that is relevant to some task performance (Jeffries, Turner, Polson & Atwood, 1981). This is perhaps the reason that mnemonic systems do not seem very useful in skills: the retrieval mechanisms have to be domain-specific because retrieval must occur when a fact is useful.

4. Further Studies of Skilled Memory

In this section we present our subsequent work in which we have attempted to expand our theory of skilled memory into other domains. Our later work has taken two courses. In one direction we have analyzed already-existing exceptional skills. We have been fortunate to be able to study two skilled individuals, a mental calculation expert (Chase, Benjamin, & Peterson, in preparation) and a waiter who remembers large numbers of orders (Ericsson & Polson, in preparation). In another direction, we have set out to study normal people in a domain where most people are skilled: sentence memory (Ericsson & Karat, 1981).

4.1. Analysis of a Mental Calculation Expert

Our subject, AB, has a magic act that he terms "mathemagics" in which he does a variety of rapid mental calculation feats. For example, he can square a 2-digit number in 1 or 2 sec, he can square a 4-digit number in about 30 seconds, and he can multiply two 2-digit numbers in about 5 seconds. These mental calculation feats are far beyond the capacity of average people as well as mathematicians and engineers. AB claims that he is the only person in the United States with such a

mathemagics act. AB's digit span is about 13 digits, for which he uses a mnemonic system (to be described later), and his performance on Luria's (1968) 50-digit matrix is also comparable to other memory experts (AB's data are reported in Table 3.)

There is a well-documented literature on mental calculation experts, or so-called "lightning calculators", most of whom lived in the last century, before the advent of mechanical calculating aids. There is a common misconception that most lightning calculators are mentally retarded or "idiot savants". Although there are a few documented cases of mentally retarded lightning calculators, most of the lightning calculators have been well- educated professionals. To take a few examples, Bidder was a very prominent British engineer, Rückle was a German mathematics professor, and the great German mathematician and astronomer Gauss demonstrated his lightning calculating ability as a boy. (See Mitchell, 1907, and Scripture, 1891, for good reviews.)

The only recent psychological study of a mental calculation expert is Hunter's (1968) analysis of professor A. C. Aitken, a Cambridge mathematics professor and perhaps the most skilled of the lightning calculators reported in the literature. Aitken's skill is based on two types of knowledge: (1) computational procedures and (2) properties of numbers. Aitken had gradually acquired a large *variety of computational procedures* designed to reduce memory load in mental computation. With years of intensive practice, these computational procedures gradually became faster and more automatic, to the point where Aitken's computational skills were truly astounding. In addition to his computational procedures, Aitken also possessed a tremendous amount of "lexical" knowledge about numbers. For example, he could "instantly" name the factors of any number up to 1500. Thus, for Aitken, all the 3-digit numbers and a few 4-digit numbers were unique and semantically rich, whereas for most of us, this is true only for the digits and a few other numbers, such as one's age. This knowledge also provides a very substantial reduction in the memory load during mental calculation.

Our subject, AB, has a typical history for a mental calculator. His interest in numbers really

began at about age 6 (he is now 20 years old), and from that time to the present AB estimates that he has averaged several hours of practice a day. During this extended period of continuous practice, AB has discovered many numerical concepts by trial-and-error. For example, at around age 12, AB discovered the algorithm he uses to square numbers, and, interestingly, Aitken was about this same age when he also discovered the same squaring algorithm.

Our analysis of AB began with his ability to square numbers, which turned out to be a fairly complex procedure. We expected, on the basis of our theory of skilled memory, that AB would use some type of retrieval structure to store the results of intermediate computations, and then he would retrieve these computations at some later point when he needed them.

Our analysis of AB's squaring procedure is based on about 10 hours of protocols, from which we derived a model, and about twenty hours of latency and error data on squaring 2- to 5-digit numbers.

The heart of AB's squaring procedure is the algorithm that reduces squaring to easy multiplication, and it is based on the following equation:

$$A^2 = (A + d)(A - d) + d^2$$

For example:

$$9^2 = 10x8 + 1^2$$

$$109^2 = 100x118 + 9^2$$

In words, the algorithm involves finding a number, d, which, when added to or subtracted from the number to be squared, A, generates a new number comprised of a single digit with trailing zeros. This in effect reduces the computation from a difficult n-digit by n-digit multiplication to a much easier 1-digit by n-digit multiplication, plus an (n-1)-digit square.

Also notice that the algorithm in recursive: an n-digit square is reduced to an easy multiplication plus an (n-1)-digit square, which in turn is reduced to an easy (n-1)-digit multiplication

plus an (n-2)-digit square, and so on. Recursion stops with 2-digit numbers because all 2-digit squares are either memorized or, in those few cases where AB claims to use the algorithm on 2-digit squares, the computations are so rapid and so familiar that they are virtually long-term memory retrieval.

To give a concrete example of how the algorithm works, consider the following 4-digit problem:

$$
\begin{aligned}
3{,}456^2 &= 3{,}000 \times 3{,}912 + 456^2 \\
&= 11{,}736{,}000 + 500 \times 412 + 44^2 \\
&= 11{,}736{,}000 + 206{,}000 + 1{,}936 \\
&= 11{,}943{,}936
\end{aligned}
$$

Notice that, as a result of the recursive process, three fairly large partial products accumulate in memory and must be added together. In general, for an n-digit square, there are n-1 partial products.

These types of mental arithmetic problems impose severe memory management problems, and from our point of view, this is what makes AB's squaring procedure interesting for our theory of skilled memory. How is it possible for AB to remember all of these numbers?

One of the first things we discovered was that AB was using a mnemonic to store these partial products. AB had previously learned a standard mnemonic technique for converting digits to consonants and making a word out of the consonants. For example, the partial product in the above example, 736, can be converted to consonants: 7 = k, 3 = m, and 6 = g, and the consonants are then converted into words, such as 736 = "key mug". Then at a later point in the problem, when AB needs to add partial products, he retrieves the mnemonic and decodes it. AB also uses his fingers as a mnemonic aid to store the hundreds digit. In the above example, AB stores the digit 9 on his fingers.

On the basis of AB's verbal protocols, we were able to derive a process model of his squaring

algorithm. With the model, we were able then to make several predictions about how fast AB would be able to solve problems of varying degrees of difficulty, and further, it gave us a way to objectively analyze the memory demands involved in squaring a number with the algorithm.

The first analysis we did was to try to account for the speed of problem solving as a function of problem size. Figure 15 shows the average time taken by AB to solve 2-digit through 5-digit squares, and Figure 15 shows these same data re-plotted as a function of the model's prediction of the number of symbols processed in working memory.

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Insert Figures 15 and 16 about here

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Several structural variables from the model were regressed against solution time: (1) number of functions in the program, (2) number of arithmetic operations, (3) number of mental operations, (4) number of chunks processed in working memory, and (5) number of symbols processed in working memory. None of these variables was able to adequately *account for the rapid increases in time with* problem size, but the two measures that did the best were number of chunks and number of symbols processed in working memory, with the latter variable (shown in Figure 16) predicting best (RMSD = 7.6 sec). The interesting fits to the data were 482 msec/symbol, 1,082 msec/chunk and 3,222 msec/mental operation. The *magnitude of these parameters* seems well in line with what is generally known about the *speed of mental operations* (Chase, 1978).

Our model, thus, seems to be a good first approximation to the speed of AB's squaring algorithm. The model still does not predict a fast-enough increase in solution time with problem complexity, however we think that most of this complexity can be accounted for with further refinements of the model. Specifically, we think that we need to measure separately the speed of the various mental operations in our model rather than simply assuming that all operations take the same amount of time. We are currently in the process of analyzing, at a finer-grain level, the basic processes of addition and multiplication, which are used in more complex procedures.

Our model also makes predictions about error rates. We found that error rate was linear with the number of arithmetic operations. According to our model, each arithmetic operation that AB performs has a 2.7% chance of an error. The overall error rates in the squaring procedure ranged from approximately 7% for 2-digit squares to approximately 45% for 5-digit squares.

The last analysis, and perhaps the most interesting analysis with respect to our theory of memory, is that of retrieval distance of various mental operations. That is, how far back does AB have to go in memory to find inputs for his mental operations This analysis has to be done within the framework of our model. That is, for problems of various size, we examined the trace of the model and computed the retrieval distance in terms of how far back in the trace were the inputs to the current operation. We generated a trace for three problems: 345^2, $3{,}456^2$, and $34{,}567^2$, and the inputs for every mental operation were classified according to how many mental operations back they occurred in memory. Figure 17 shows the frequency of retrieval distance in operations; the distributions for the three problem sizes were combined because they were indistinguishable. Inputs that required decoding a mnemonic or other external memory aid are indicated in the figure with a dot.

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Insert Figure 17 about here

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There are a couple of interesting things to notice about these data. First, most of the inputs for mental operations come from very recent mental operations. In fact, over half of the inputs for a mental operation come from the immediately preceding operation. Second, those inputs that were stored and retrieved with the aid of a mnemonic are retrieved over much longer distances.

From the analysis, we were surprised at how AB's squaring procedure keeps the inputs for operations close in time. That is, AB's squaring procedure seems to have been designed to minimize the working memory demands by deriving inputs to mental operations from immediately preceding operations. Even so, the squaring procedure is too complex to keep everything in short-term

memory. It is simply the case that partial products must be stored for fairly long periods of time (and with many intervening mental operations) before they are needed again. Under these circumstances, AB has resorted to mnemonics. Finally, we point out that even though the logic of AB's squaring algorithm is recursive, recursion is very expensive in terms of memory load. AB has devised a complex procedure, the logic of which is iterative rather than recursive, to avoid the memory problems associated with recursion.

4.2. The Memory of a Waiter

Ericsson & Polson (in preparation) have studied a waiter (JC), who is able to take up to 17 menu orders without any form of memory aid. The main focus of this research has been to describe the performance of this waiter in an experimentally controlled environment and describe the cognitive processes and structures underlying this memory feat.

The initial phase of this study was concerned with finding an experimental analog of the restaurant environment. The people at the table in the restaurant were simulated by pictures of faces, and the order was read by an experimenter as the waiter pointed to the corresponding picture. To mimic the restaurant situation JC was allowed to ask for repetitions of items. JC controlled the rate at which he took orders, and he was timed until he signalled the experimenter that he was ready to recall.

Each order consisted of a main course of a meat dish (8 alternatives) cooked to a certain temperature (5 alternatives) with a starch (3 alternatives) and a choice of salad-dressing (5 alternatives) and during the first part of the experiment also a beverage (9 alternatives). The beverage item was later omitted because JC argued that beverage orders are taken separately for dinners. Orders were generated randomly by a computer-program.

According to our subject (JC) the experimental situation is much harder than the restaurant situation because of the randomness of orders. In the restaurant situation only a relatively small number of the possible combinations are frequent.

The experimental sessions consisted of two blocks, each consisting of an order of 3, 5 or 8 people in random order. JC was instructed to proceed as rapidly as possible without making errors when recalling the collection of orders. During some sessions JC was instructed to "think aloud" while doing the same task. JC was also tested for his memory of the orders at the end of the experimental session.

Even though our experimental analysis of JC's memory skill is not yet completed, we have found considerable evidence for the skilled memory mechanisms described earlier. In our laboratory situation we were able to show that JC was able to perform the memory task with few, if any, errors in recall. The average presentation time of the first five sessions (5 items/order) is given in Figure 18. In the same figure we have plotted the average times for Sessions 12 - 14 and Sessions 24 - 32, which are both based on 4 items per order.

The presentation time is short and for the sessions with most practice it approaches the reading time for orders from a table of 3 people. We can also see a reliable decrease in presentation time as a function of practice. It may appear somewhat unexpected to find such a large speed-up given that JC has been taking orders without notes for several years prior to the experimental sessions. However, there appears to be little pressure for increasing encoding speed in the restaurant situation beyond the rate people are able to generate orders, and this rate is relatively slow.

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Insert Figure 18 about here

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One of the difficulties in remembering dinner orders for normal people is the similarity between the orders. One of the essential components in JC's memory skill is his procedure for avoiding interference, which in fact capitalizes on the redundancy created by similar items. From our thinking aloud protocols it is clear that JC at the time an order for a person is read to him reorganizes this information into sub-lists with items of a given category. Each sub-list contains 4 items or less. For salad dressings JC uses the initial letters and searches for patterns or meaningful abbreviations or

words. For example, once JC encoded "Blue cheese - Oil and vinegar - Oil and vinegar - Thousand islands" as B - O - O - T or "boot". For temperatures, JC is sensitive to the dimension of rareness, which ranges from rare to well-done, and encodes progressions and other types of patterns, as well. There are only three different kinds of starches and therefore there is a high probability of occurence of some kind of pattern. JC encodes many other kinds of information about "spatial" position of the person making the order and relationships between the ordered items and the person making the order. However, the within-category encoding appears to be his principal means of encoding.

One piece of evidence for JC's coding strategy comes from the order in which he gives his immediate recall. In recalling orders from tables with 5 and 8 people he does not preserve the presentation order of the items. Instead, JC recalls all salad dressings first and then all entrees, temperatures and starches. For a table of 3 persons JC originally recalled the information as presented, i.e. entree, temperature, starch and salad-dressing for each order before moving on to the next order. Recently, JC has changed to within-category recall even for 3-person orders.

We are now in the process of conducting experiments designed to demonstrate the priority of the within-category encoding more directly. We have also studied JC's memory for orders after the session. After Session 1 we reconstructed the pictures corresponding to the first table of 5 people, and JC could accurately recall 10 items or 40 % of the presented items. He recalled the encoding for the salad-dressings (COOBB) and a few isolated items but not a single complete order. Then we reconstructed the second and last table of 5 persons, and JC recalled the presented information perfectly.

There is suggestive evidence that a subsequent encoding of an order from a table with the same number of people leads to reduction of memory for the initial encoding. After session 3 we asked JC to recall as much as possible about salad-dressings. From the most recent set of table sizes (Block 2) JC recalled 14 items (88 %) without regard to order, or 11 items (69%) if the order within a table has to be exactly correct. From the first block of tables JC recalled 4 items (25 %). It should be

noted that a similar low level of recall might have been obtained for our digit-span experts if they had to rely on episodically based recall.

4.3. Sentence Memory

Most of the above demonstrations of skilled memory refer to skills that only a small portion of the general population ever acquire. This raises the issue of whether all adults are able to acquire and exhibit skilled memory. To address this concern Ericsson and Karat (1981) set out to search for evidence of skilled memory in a domain where all adults have developed a skill. The most obvious skill that all normal adults have is their ability to comprehend and generate meaningful language. In most respects we can compare the language skills of any human adult with other complex skills, like chess. To make our study as directly comparable to the earlier work of Chase and Ericsson we decided to use the methodology of measuring memory spans. We read sequences of words to subjects for immediate verbatim recall. We wanted to demonstrate an analogous finding to the one by Chase and Simon (1973a), that for scrambled chess pieces on a chessboard the chess master is no better than a novice in immediate recall of chess-boards. We thus compared subjects immediate recall for meaningful sentences with the same words presented in a random scrambled sequence.

From a rather extensive literature we know that normal subjects' memory spans for unrelated words is on the average six words. Although we have not been able to find any attempts to measure peoples' memory spans for meaningful sequences of words, i.e., sentences, it is clear from several studies and experiments that the span should be considerably higher, 10-12 words or more.

The class of meaningful sentences is not well-defined, so we did not attempt to generate the sequences. Like other investigators of skilled performance we collected instances, i.e., sentences, from real-life. We sampled sentences of different length from two sources. The first source was two collections of short-stories. The second source was three novels by Steinbeck. We copied these sentences and only substituted pronouns for names. We generated scrambled word-sequences by randomizing the order of words in these selected sentences.

The subjects were first given a series of sentences, and then a series of scrambled sequences. All sequences of words were read at a constant rate (1 word/sec) in a monotone voice except for the last word, which was stressed to signal the subjects to write the sequence down verbatim. In Figure 19 we have plotted the percent perfectly recalled sequences as a function of number of presented words. (Each point corresponds to averages based on more than 15 subjects responses to five or more different sequences; for more details see Ericsson and Karat (1981)).

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Insert Figure 19 about here
....

A measure of memory span is the number of words an "average" subject will correctly recall half of the time. The memory span for scrambled sequences is between 6-7 words, whereas the memory span for meaningful sequences, i.e., sentences, is about 14 words. The difference is, of course, statistically reliable.

4.3.1. coding

There are some interesting results giving support for the hypothesis that the words are not encoded and stored as units, but rather encoded in some other form.

The almost linear relationship between number of words in a sentence and percent recall was based on averages over many sentences. Among these sentences we can find individual sentences for which this relationship doesn't hold. We found exceptionally difficult shorter sentences, such as the following 12-word sentence that less than a third of our subjects recalled correctly:

"He had won a few dollars from a guard on the flatcar".

(The underlined words were frequently altered, with the rest of the sequence recalled correctly.) On the other hand, several sentences with 20-words were recalled correctly by more than half of our subjects. In a subsequent experiment we included sentences of up to 30 words in length. One of the 26-word sentences was recalled correctly by four of the subjects, and the following 28-word sentence was recalled correctly by two subjects:

"She brushed a cloud of hair out of her eyes with the back of her glove and left a smudge of earth on her cheek in doing it."

Further evidence is obtained from a preliminary analysis of errors. Subjects virtually always recall sentences that are semantically consistent with the presented sentence. Most errors concern lexical substitutions without effect on meaning, like exchanging definite and indefinite articles and exchanging prepositions. Sometimes modifiers, like adjectives and adverbs, are omitted.

4.3.2. Post-Session Recall

In one experiment we wanted to test subjects' incidental long-term memory for presented sentences, for which substantial memory would be expected, versus scrambled words, for which little or no memory would be expected. We alternated sentences and scrambled sequences and asked for immediate written recall after each sequence. The major difference from earlier experiments was that we asked the subjects unexpectedly for cued recall of all the presented information afterwards. A unique word from each sentence and each scrambled word-sequence was presented in random order. Subjects were asked to recall as much as they could about the corresponding sequence. They were asked to underline those parts of sequences they felt confident were verbatim.

The main result from this experiment is that subjects' cued recall of the sentences is remarkably high and their recall of scrambled word-sequences is essentially none. Only in 12% of the cases could subjects recall anything from the scrambled sequences and in only 4% of the cases were they able to recall more than a single word. In contrast, sentences were recalled in 79% of the time, with subjects being mostly able to recall more than half of the presented words. This clearly suggests to us that a single cue-word was able to access an integrated representation rather than just a single chunk or sub-unit.

In a pilot study subjects were only given a free-recall instruction, and these subjects were only able to recall a few sentences. The superiority of cued-recall indicates some interesting restrictions on when memory for the sentences can be accessed and used.

Another aspect of skilled memory was demonstrated in this experiment, namely the ability to monitor the correctness of one's memory. Recall was almost 90% for words that subjects underlined to mark confidence that these words were verbatim. The corresponding percentage for words not underlined was only about 55%. This shows a highly reliable ability to assess correctness of recall. In another experiment we had subjects underline verbatim parts of their immediate recalls. Underlined words were correct 96% of the time and not underlined words were correct 75% of the time.

4.3.3. Individual Differences

In our experiments we have also consistently found systematic individual differences in ability to recall sentences. Using traditional methods for calculating span we find span for words in sentences to range from about 11.0 to about 20.5 words for different subjects. When we analyze our data in terms of number of perfectly recalled sentences or percent recalled words we find reliable individual differences as well.

In the last experiment we attempted to explore the source of the reliable individual differences in span or ability to recall. According to the skilled memory model the best predicter of somebody's ability to recall sentences verbatim is their level of language skill, which we attempted to assess by a test measuring correct language use and a test of verbal reasoning. To evaluate mediation of general achievement and intelligence, subjects were also given a test of numeric reasoning. Following our earlier procedure we had subjects recall sentences and scrambled words. A regression analysis showed that the number of perfectly recalled sentences could best be predicted by a linear combination of language skill scores and the number of perfectly recalled scrambled sequences. It is interesting to note that language usage and verbal reasoning were unrelated to recall of scrambled sequences, which suggests that at least two independent factors underlie the ability to recall sentences: language skill and efficiency of rehearsal.

Conclusion

In our work over the past three years, we have tried to discover the cognitive mechanisms underlying skilled memory performance. We have shown that skilled individuals are able to associate

information to be remembered with their large knowledge base in the domain of their expertise, and further, they are able to index that information properly for later retrieval. In addition, Practice storing and retrieving information causes these processes to speed up.

The major theoretical point we wanted to make here is that one important component of skilled performance is the rapid access to a sizable set of knowledge structures that have been stored in directly retrievable locations in long-term memory. We have argued that these ingredients produce an effective increase in the working memory capacity *for that knowledge base*.

The question arises as to what exactly is working memory? In part, there is a problem of definition, and in part there is still considerable doubt about the mechanisms of working memory. For the sake of terminology, we want to suggest that working memory has at least the following components: (1) short-term memory, which provides direct and virtually immediate access to very recent or attended knowledge states, (2) intermediate-term memory, the task-specific retrieval structure in long-term memory, which provides direct and relatively fast access to knowledge states, and (3) context, which contains structures for controlling the flow of processing within the current task and provides relatively fast and direct access to knowledge structures relevant to the current task and context. The auditory and visual-spatial buffers are also important components of working memory, although they are not the focus of this article. The main thrust of our paper has been on the important role of retrieval structures as working memory states.

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Footnote

[1] Sadly, SF died of a chronic blood disorder in the Spring of 1981.

Figure Captions

1. Average digit span for SF and DD as a function of practice.

2. Average percent after-session recall for SF and DD as a function of practice.

3. Development of SF's retrieval structure. On the left is shown the session number in which the retrieval structure was first reported, and on the right is shown the range of digits over which the retrieval structure works. Squares linked together correspond to supergroups, and inside each square is the number of digits corresponding to that group. The circled R corresponds to the rehearsal group of 4 to 6 digits.

4. SF's retrieval structure for 80 digits and DD's retrieval structure for 69 digits.

5. Inter-group times for SF and DD as a function of list size and practice. The dependent variable is the time that subjects paused between groups when they controlled the visual presentation of digits.

6. A comparison between SF (open squares) and Professor Ruckle (circles). Shown is the time required to memorize visually presented digits as a function of number of digits. SF's data are taken from the experiment on the Luria matrices (Table 3), and Ruckle's data are derived from Muller (1911).

7. DD's semantic network of 1-mile times over the range of 346 to 420, derived from Table 2.

8. Latency to name the missing digit as a function of the location of the missing digit in the probe. The location of the missing digit is indicated at the bottom of the figure. Open squares represent 3-digit probes, and darkened squares represent 4-digit probes. Brackets represent ± 1 standard deviation, based on 10 or fewer observations.

9. DD's memory trace for the 1-mile time 4:05.4. Stored with the trace are semantic features describing the trace as a running time, features describing its location in the retrieval structure, and features corresponding to the current context. Included in the context are local features describing the decimal point as well as noticed relationships between the trace and other near-by digit groups, and global features describing noticed relationships between the trace and earlier digit groups, the trial number, and other global contextual features.

10. Schematic representation of retrieval of the memory trace. The trace is accessible through its semantic code, its location in the retrieval structure, and through the context.

11. SF's system for coding digits, derived from his verbal protocols.

12. Percent correct recall for a trial as a function of the trial number, for both SF and DD for the last 100 sessions. The standard error for these percentages, based on 100 observations, is about 5%.

13. Time between the last presented digit and the first recalled digit as a function of trial number for each subject. For the eight data points above, the average S.D., based on the

last 100 sessions, is 33 sec, and the average S.E. is 4.2 sec.

14. Percent correct recall of digit groups after the session as a function of trial number for SF (sessions 99-108) and DD (sessions 111-120). The standard error for these percentages, based on slightly more than 100 observations, is about 5%.

15. AB's average solution time for squaring numbers as a function of number of digits. Brackets are S.D.s of averages for 17 days. (S.D.s for 2 and 3 digits -- .2 and 1.0 sec, respectively -- are too small to be shown.) Each daily average is based on 7 or 8 observations and each total mean is based on about 130 observations.

16. Observed and predicted solution time as a function of number of symbols processed in working memory.

17. Frequency distribution of predicted solution time as a function of retrieval distance for AB's squaring algorithm. These frequencies are derived from three problems: 345^2, 3456^2, and 34567^2. X's are retrievals without mnemonic aids, and dots are retrievals with the aid of a mnemonic.

18. Speed of taking orders for the skilled waiter. The S.E.s for the above points range from 1.5 sec to 13.8 sec and the average S.E. is 6.5 sec.

19. Percent correct recalled scrambled sequences as a function of the number of words in each sequences.

TABLE 1

MAJOR CODING STRUCTURES

	Coding structure	Example	First Reported (Session No.)
3-digit groups	Time	8:05	5
	Age + Decimal	49.7	70
4-digit groups	Time (3,4,5,10 mt)	13:20	20
	Time + Decimal	4:10.6	26
	Digit + Time	9-7:05	60
	Year	1955	64
	Age + Age	46 76	64

TABLE 2

SF's and DD's Categories for Times Between 3:40 and 4:20

SF's Category Times	DD's Categories Times	Description of Semantic Category
	340-344	Slow 3/4-mile times
349	346-349	Coe & Ovett. I imagine a picture I saw in a magazine with Coe or Ovett and 348 on it.
	347.	347 point something is the new world record
	349.	John Walker. With a decimal time, I think of John Walker in a race. Without a decimal, I picture Coe or Ovett.
350	350	New Barrier
351	351	Old World Record for a long time
	352	Indoor World Record
	353	Darrell Waltrip
352-358		
	354-356	Now middle-of-the-pack in a great race
	357-359	Breaking the 4-minute mile
359		
400	400	Still the Big Barrier
	401-402	A second or two off the 4-minute mile
401-414		
	403-412	Seems like everyone has run one of these
415		Every good college miler has done a 40-somethir
416-419	413-420	Teens. Usually associated with high school times.
420		

TABLE 3

STUDY AND RECALL TIME (SEC)

on Luria's 50-digit Matrix

	SKILLED SUBJECTS								UNSKILLED SUBJECTS					
	SF	SF 1 year later	DD	AB	Luria's S	Hunt & Love's VP	$\overline{X}$	S.D.	S_1	S_2	S_3	S_4	$\overline{X}$	S.D.
Study Time	187	81	193	222	180	390	209	101	798	1240	685	715	860	258
Recall Time														
Entire matrix	43	57	38	51	40	42	45	7.3	77	95	42	51	66	24
Third Column	41	58	68	56	80	58	60	13.0	125	117	42	78	90	38
Second Column	41	46	28	40	25	39	36	8.2	81	110	31	40	66	37
Second Column up	47	30	27	54	30	40	38	10.9	112	83	46	63	76	28
Zig Zag	64	38	41	52	35		46	11.9	123	107	78	94	101	19

TABLE 4

Percentage of Item and Order Errors

Percent
Errors

	ITEM	ORDER
SF	82	18
DD	71	29

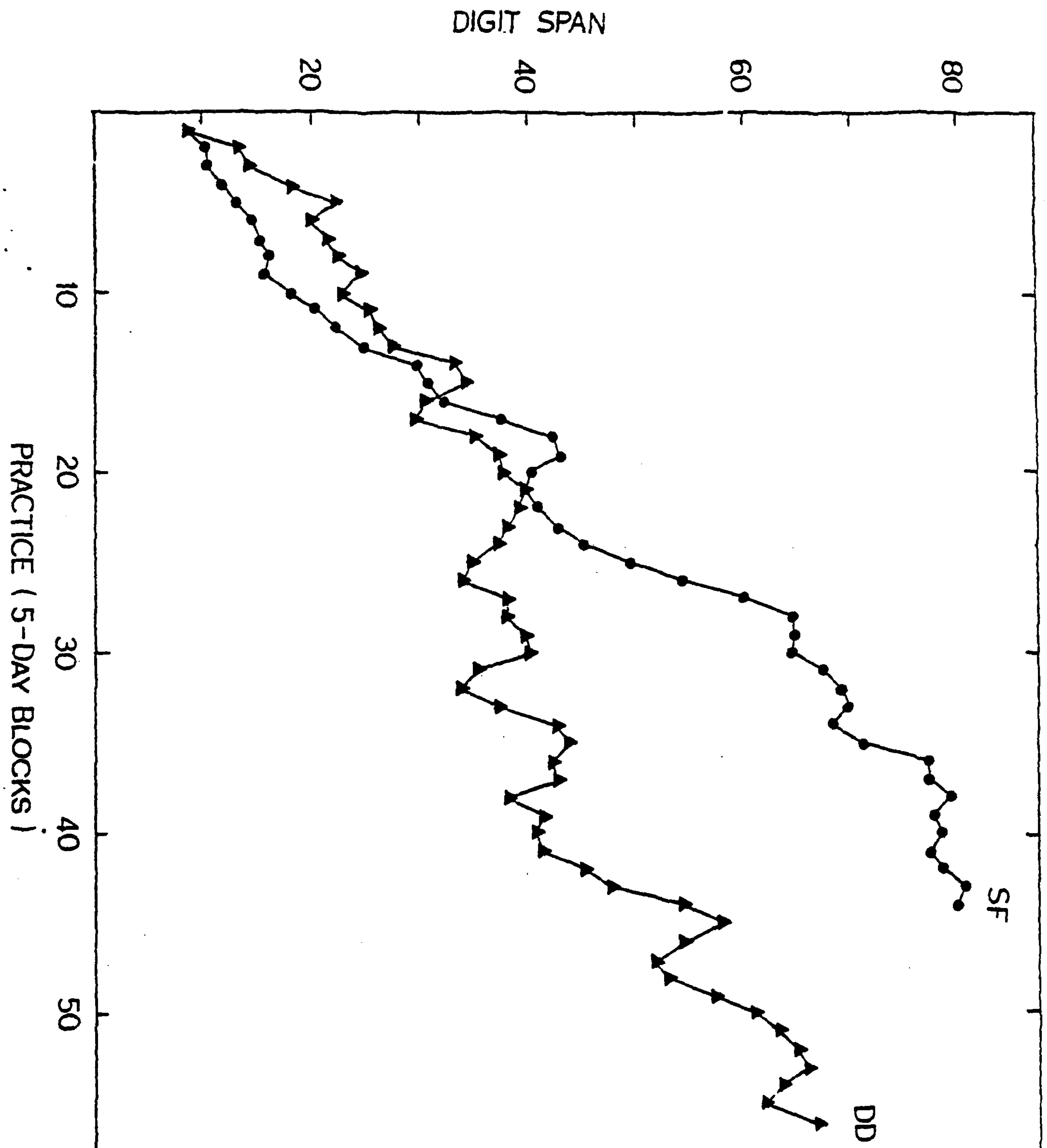


Figure 1

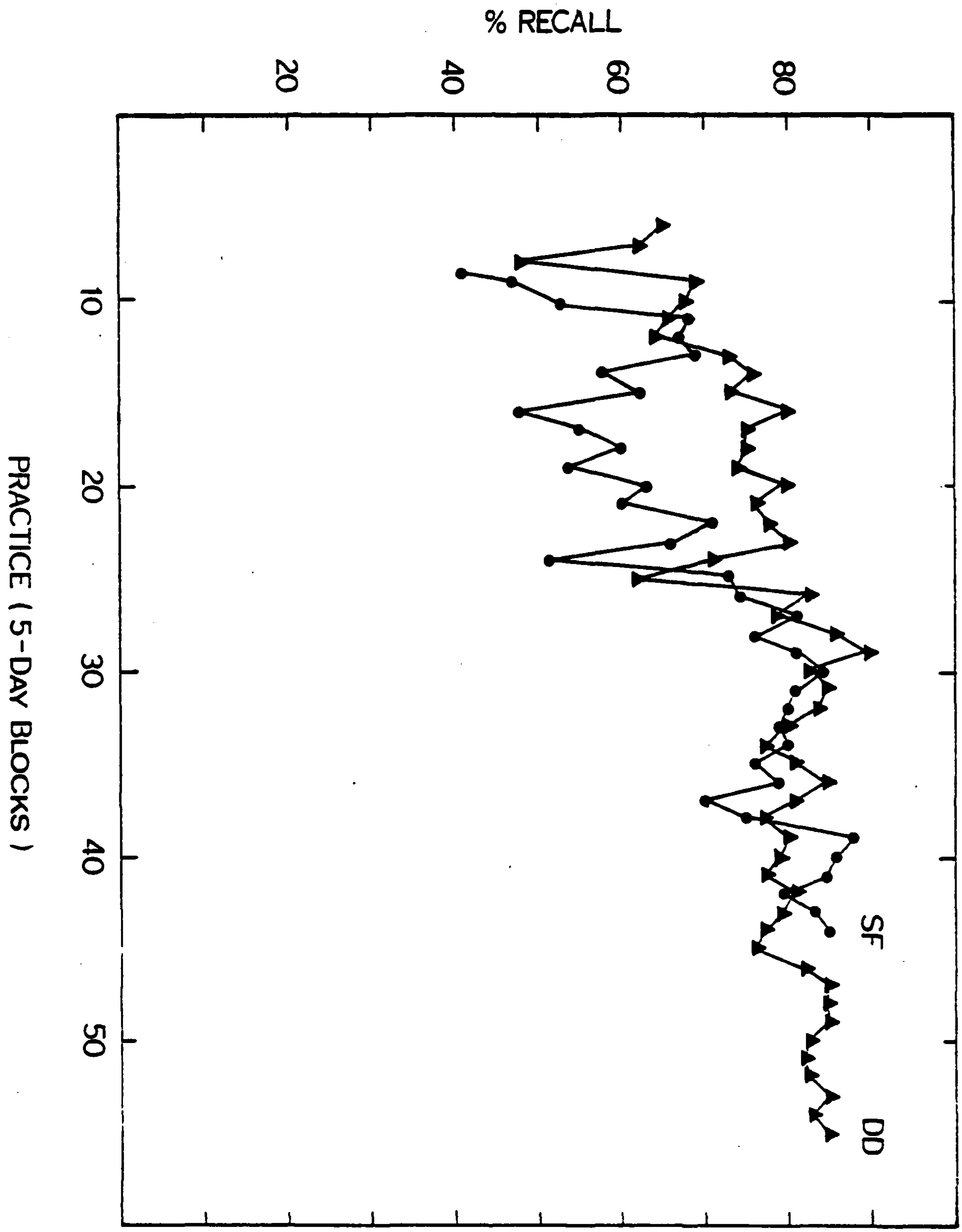


Figure 2

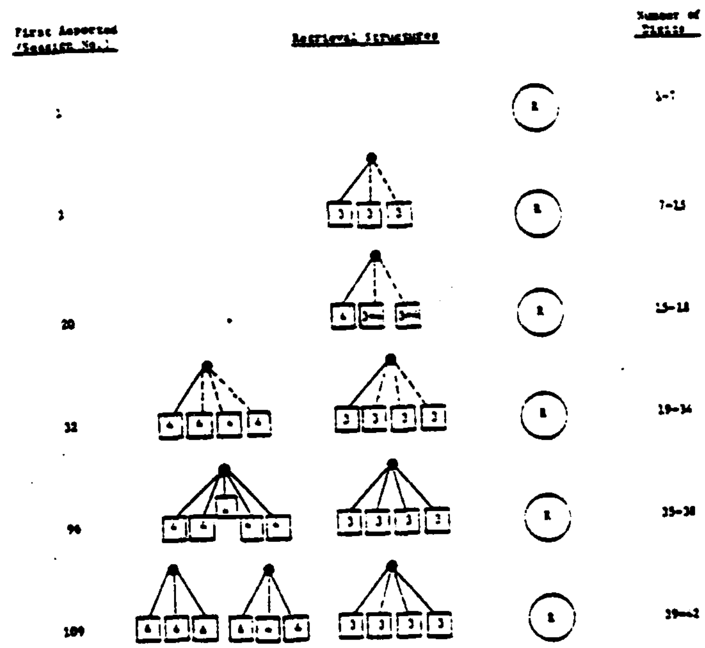
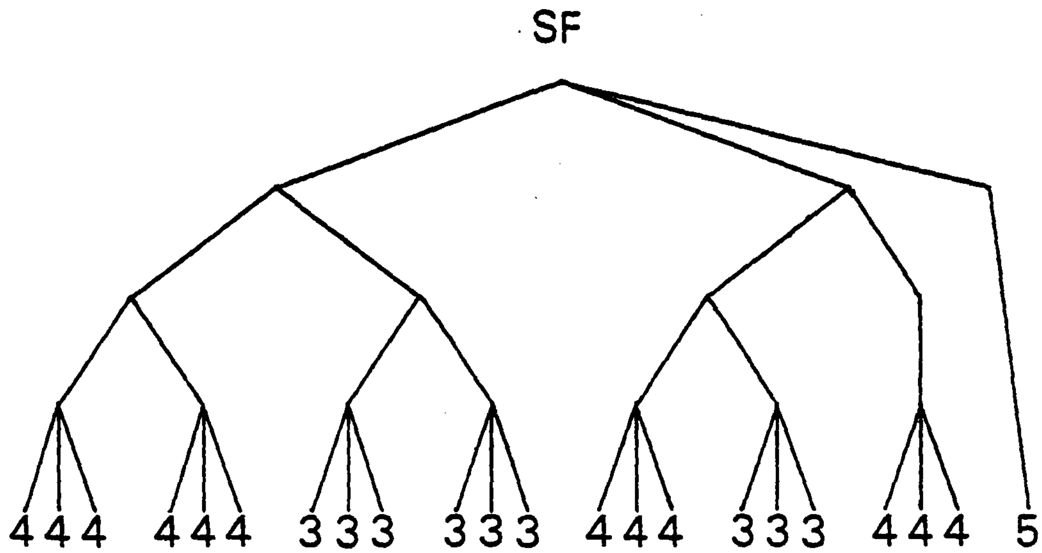


Figure 3



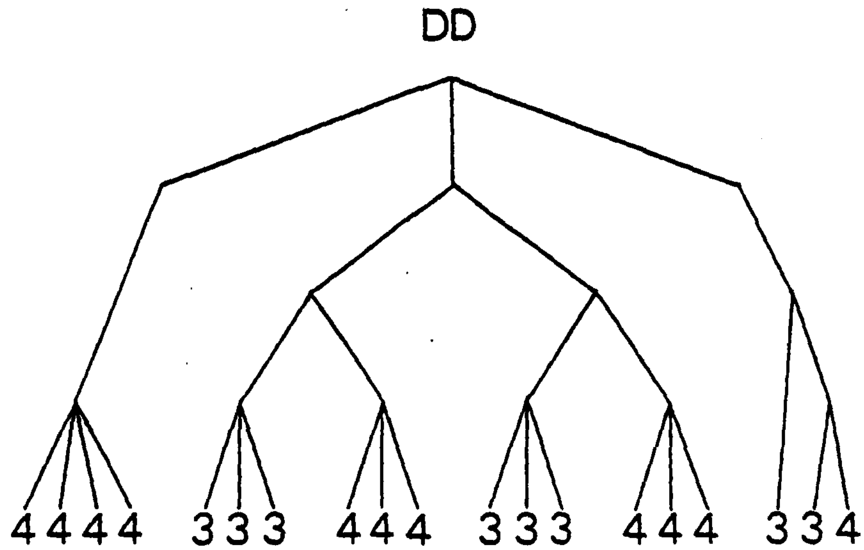


Figure 4

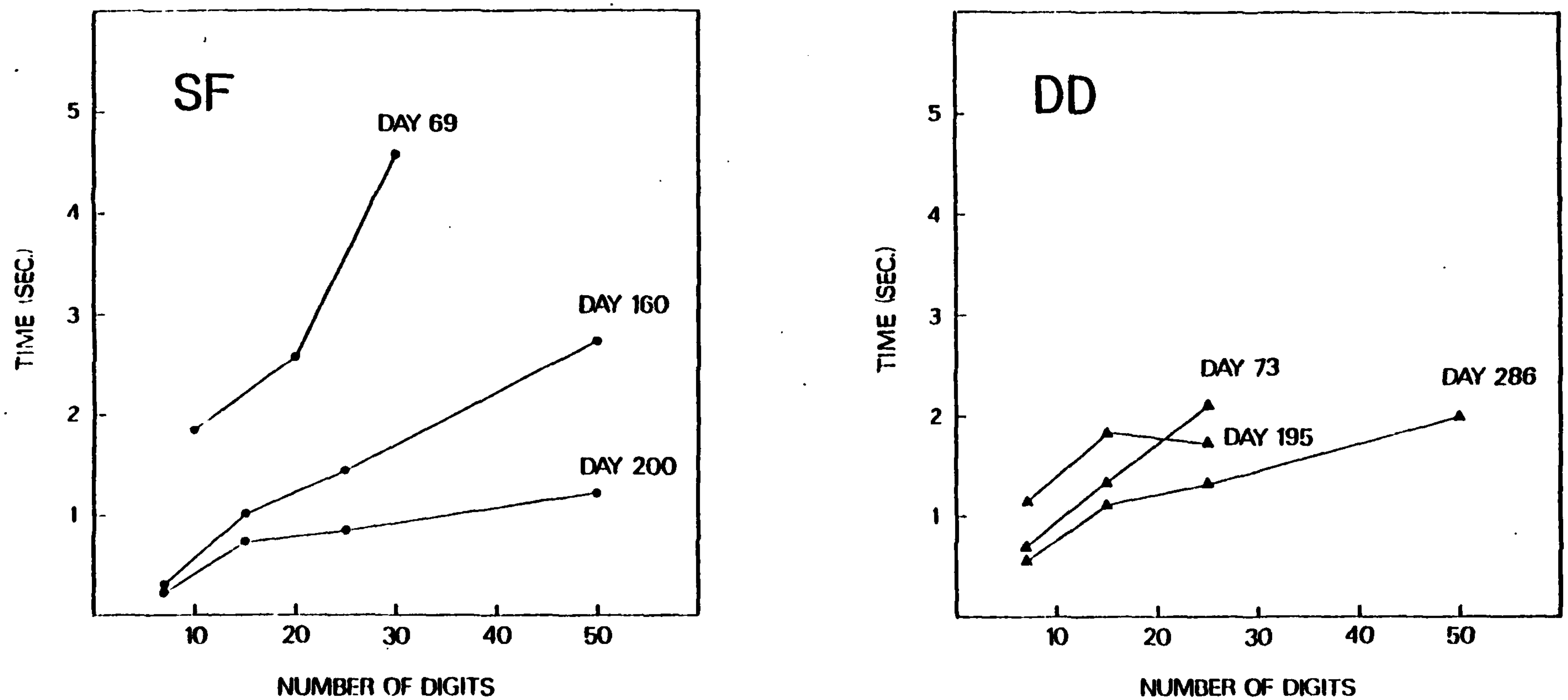

SF
DAY 69
DAY 160
DAY 200
TIME (SEC.)
5
4
3
2
1
10
20
30
40
50
NUMBER OF DIGITS
DD
DAY 73
DAY 195
DAY 286
TIME (SEC.)
5
4
3
2
1
10
20
30
40
50
NUMBER OF DIGITS

Figure 5

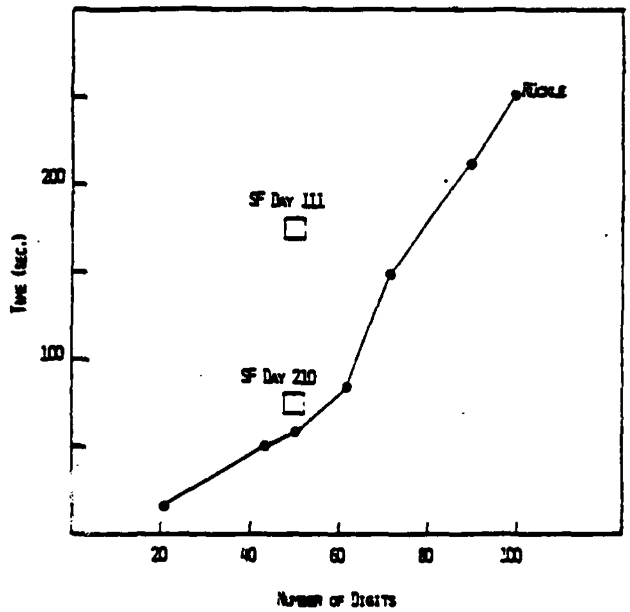

SF Day 111
SF Day 210
200
100
Time (sec.)
20
40
60
80
100
Number of Digits

Figure 6

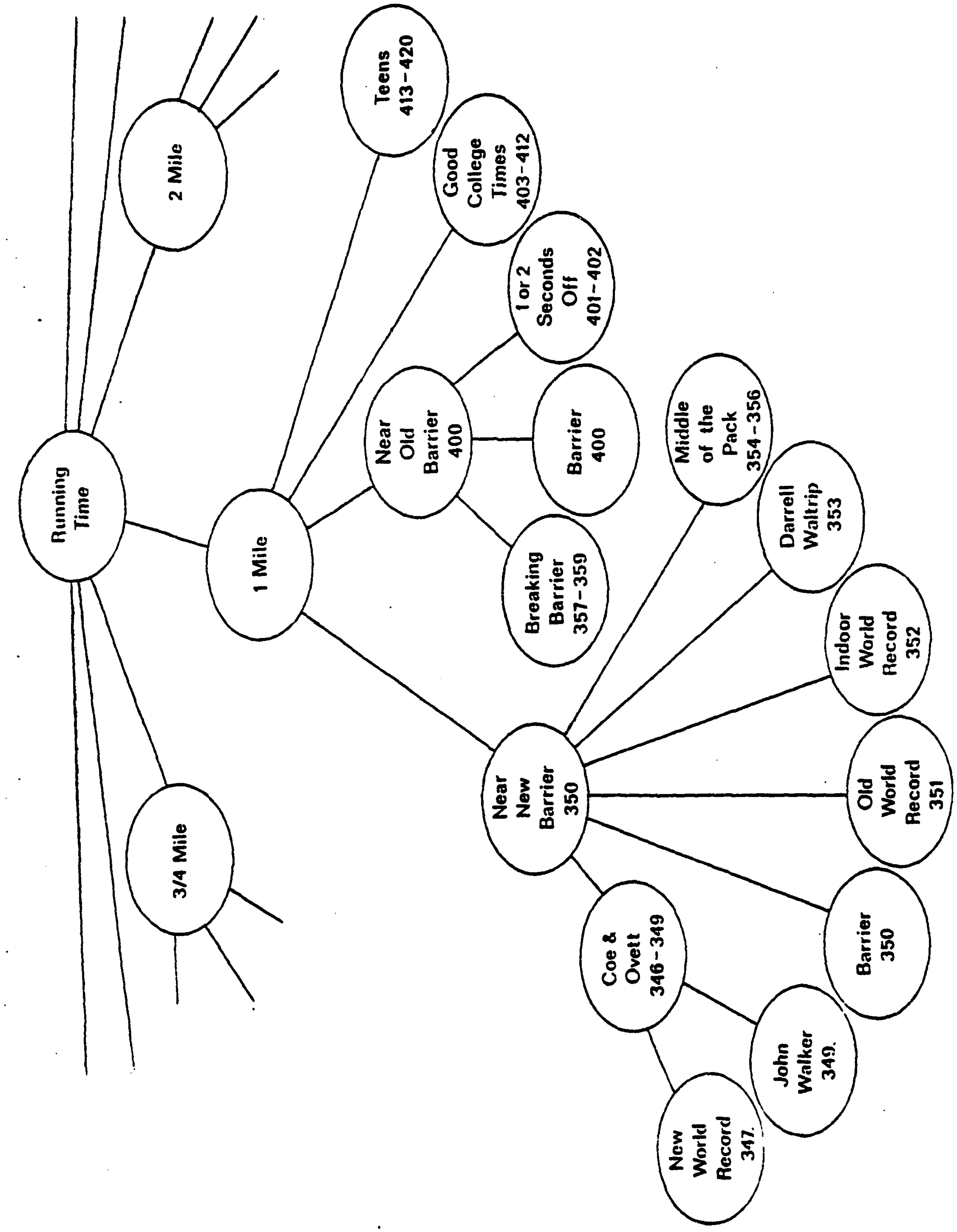

Running Time
2 Mile
1 Mile
3/4 Mile
Teens 413-420
Good College Times 403-412
1 or 2 Seconds Off 401-402
Near Old Barrier 400
Barrier 400
Breaking Barrier 357-359
Near New Barrier 350
Middle of the Pack 354-356
Darrell Waltrip 353
Indoor World Record 352
Old World Record 351
Barrier 350
Coe & Ovett 346-349
John Walker 349
New World Record 347

Figure 7

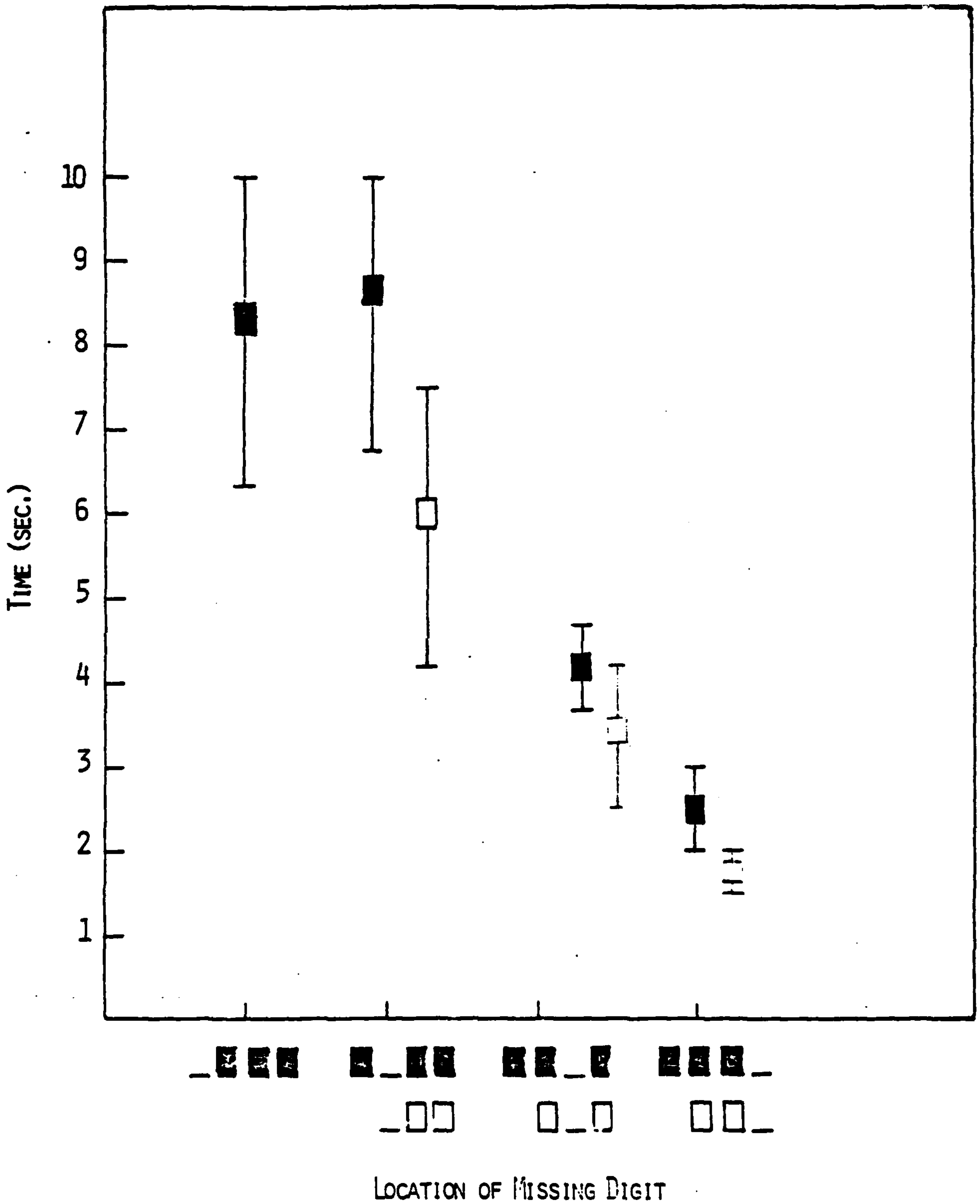


Figure 8

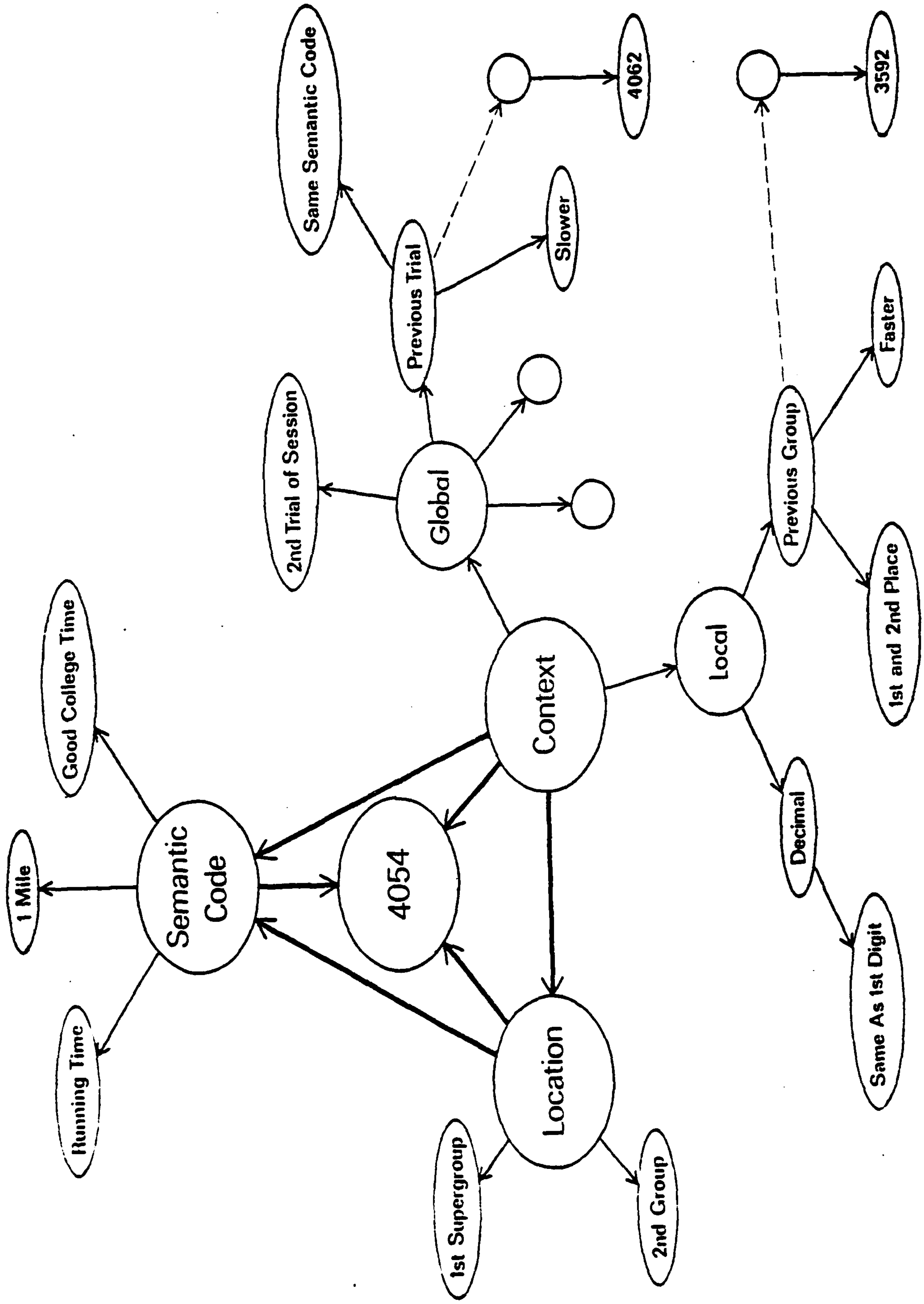

Context
Semantic Code
4054
Location
Global
Local
1 Mile
Running Time
Good College Time
2nd Trial of Session
Previous Trial
Same Semantic Code
Slower
4062
Previous Group
Faster
1st and 2nd Place
3592
Decimal
Same As 1st Digit
1st Supergroup
2nd Group

Figure 9

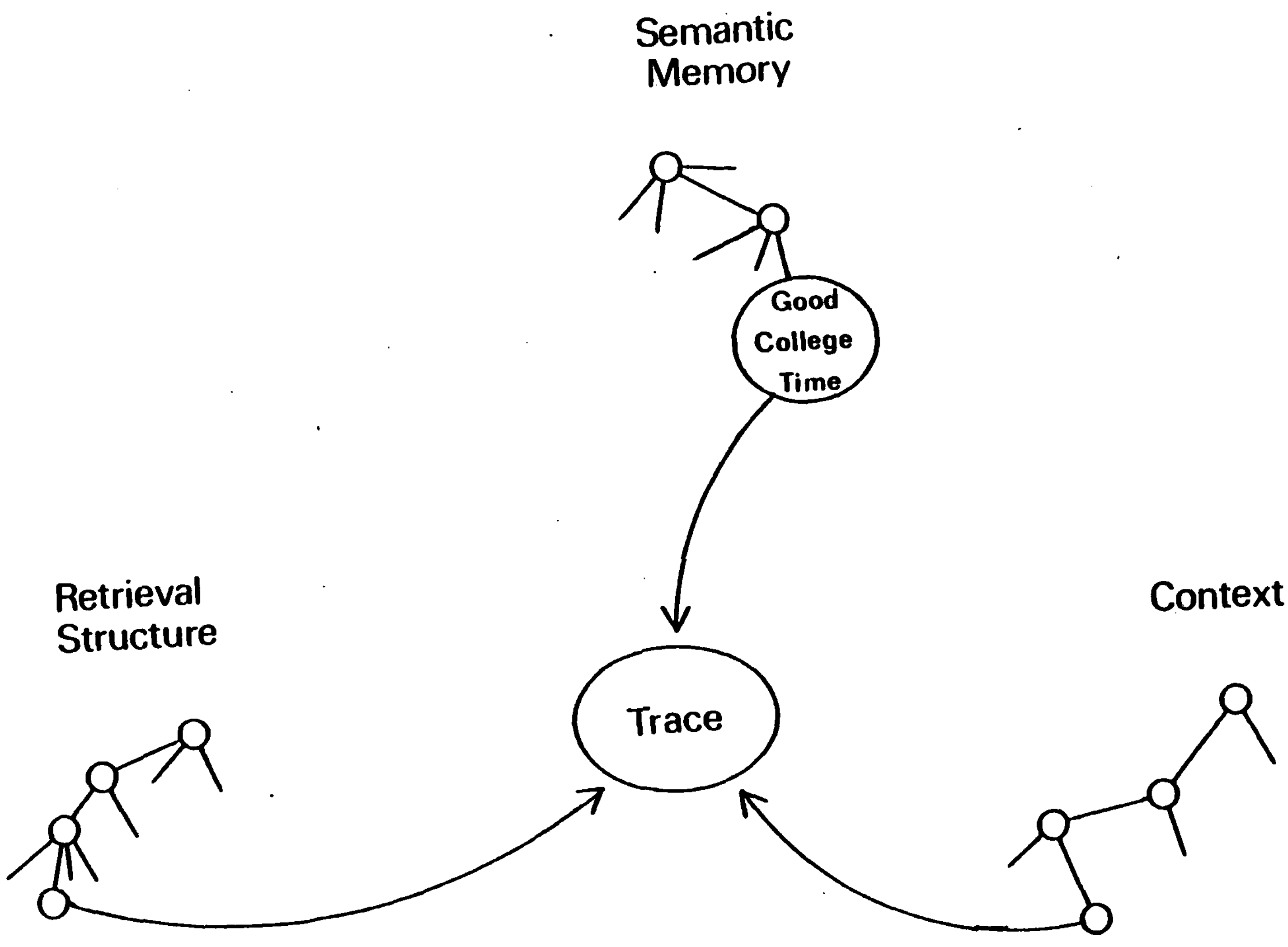

Semantic
Memory
Good
College
Time
Retrieval
Structure
Trace
Context

Figure 10

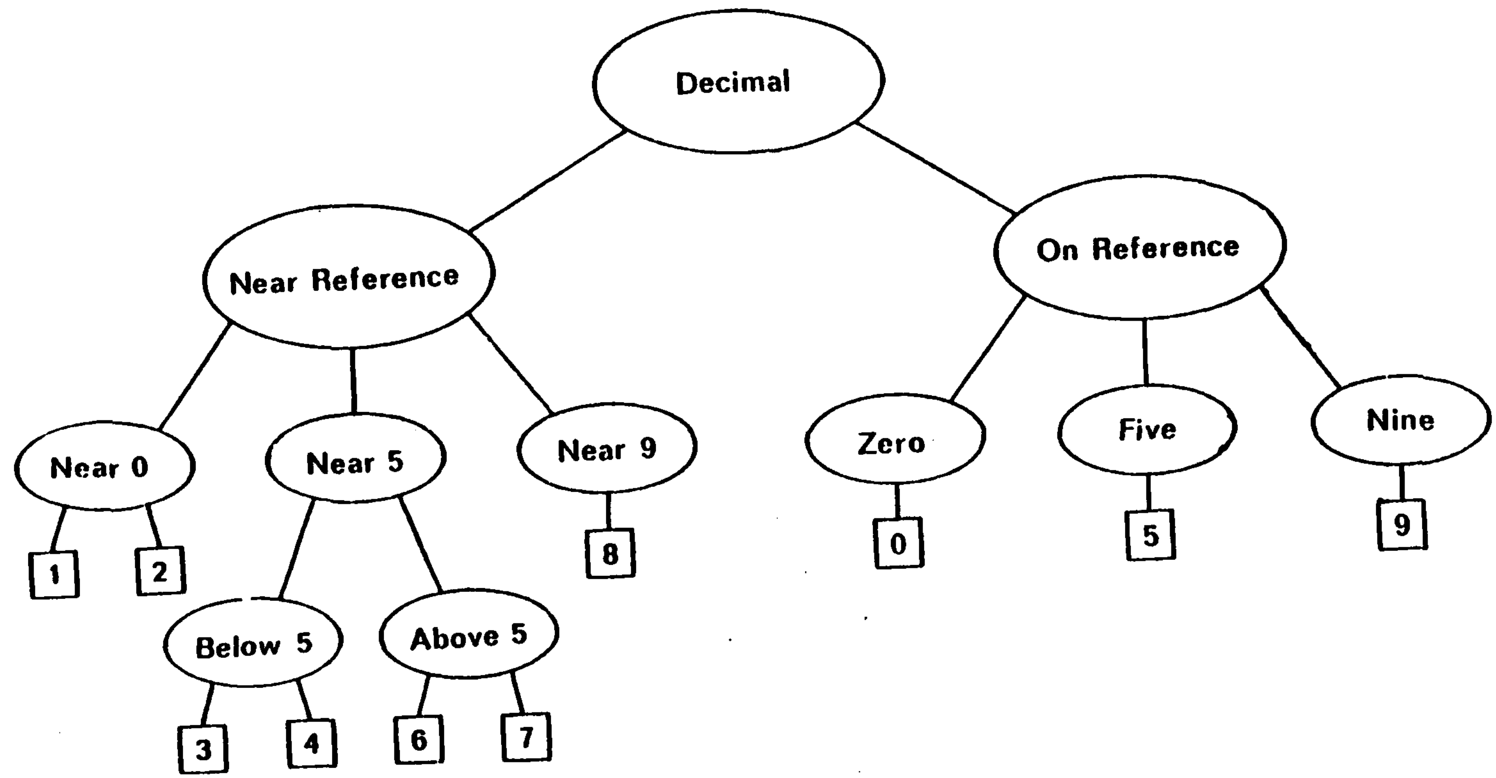

Decimal
Near Reference
On Reference
Near 0
Near 5
Near 9
Zero
Five
Nine
1
2
8
0
5
9
Below 5
Above 5
3
4
6
7

Figure 11

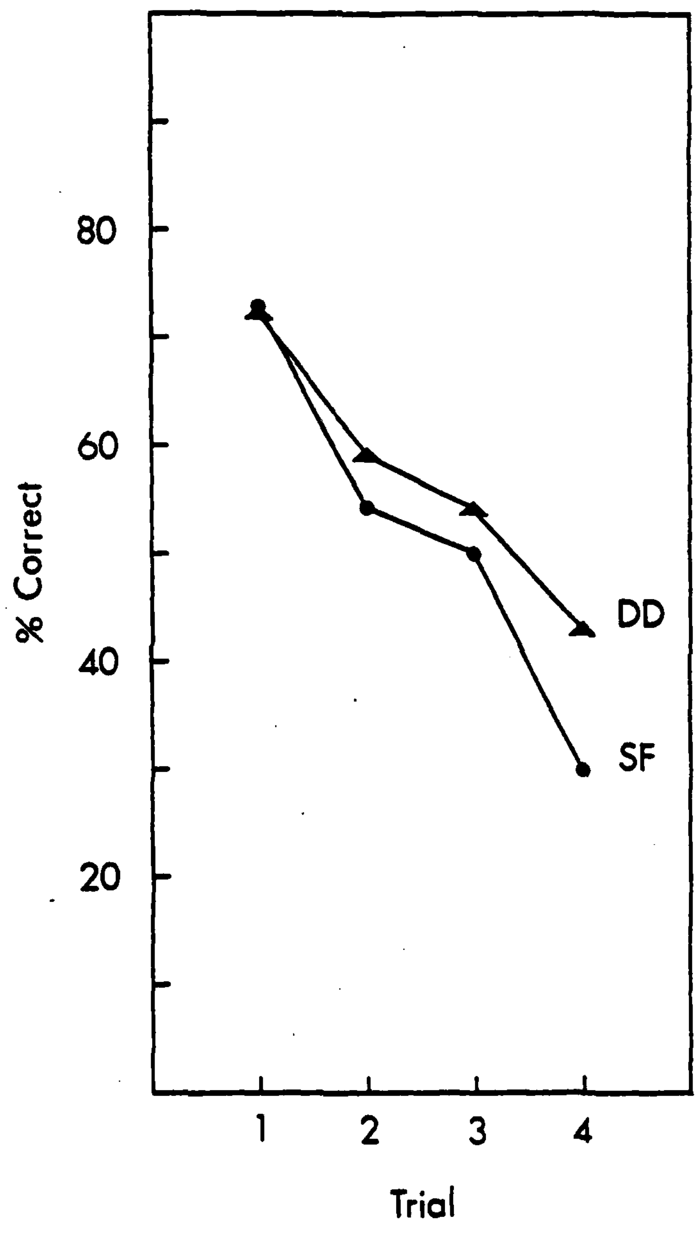


Figure 12

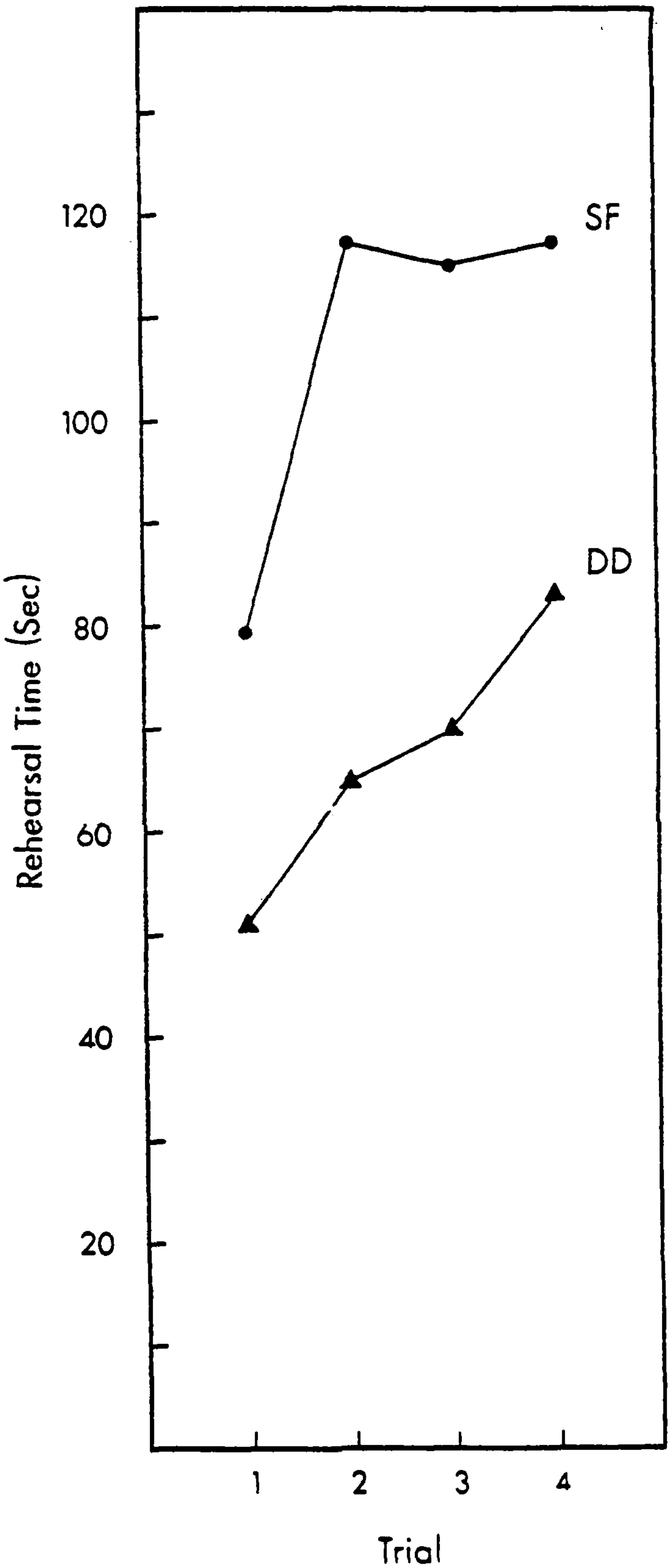


Figure 13

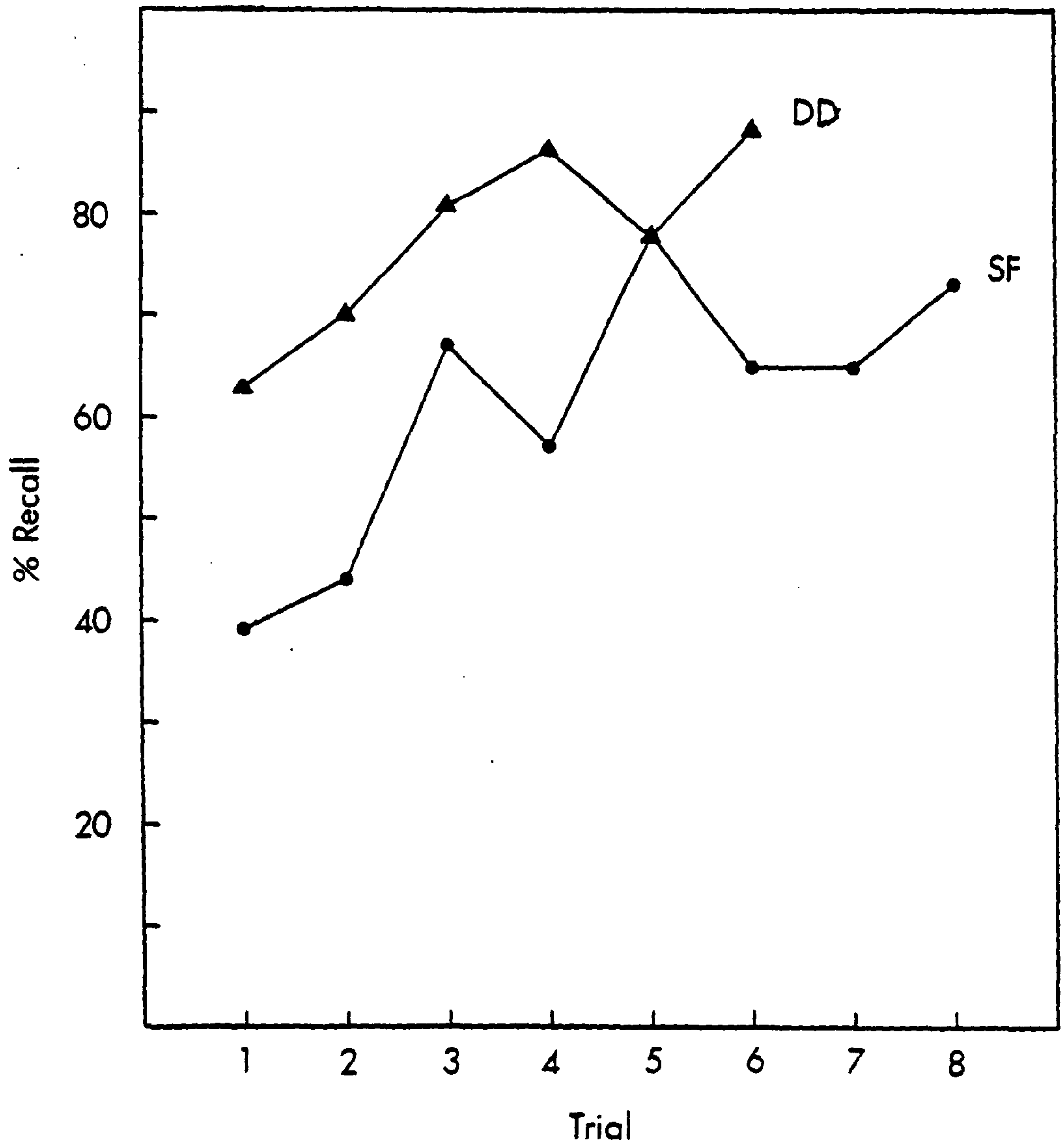


Figure 14

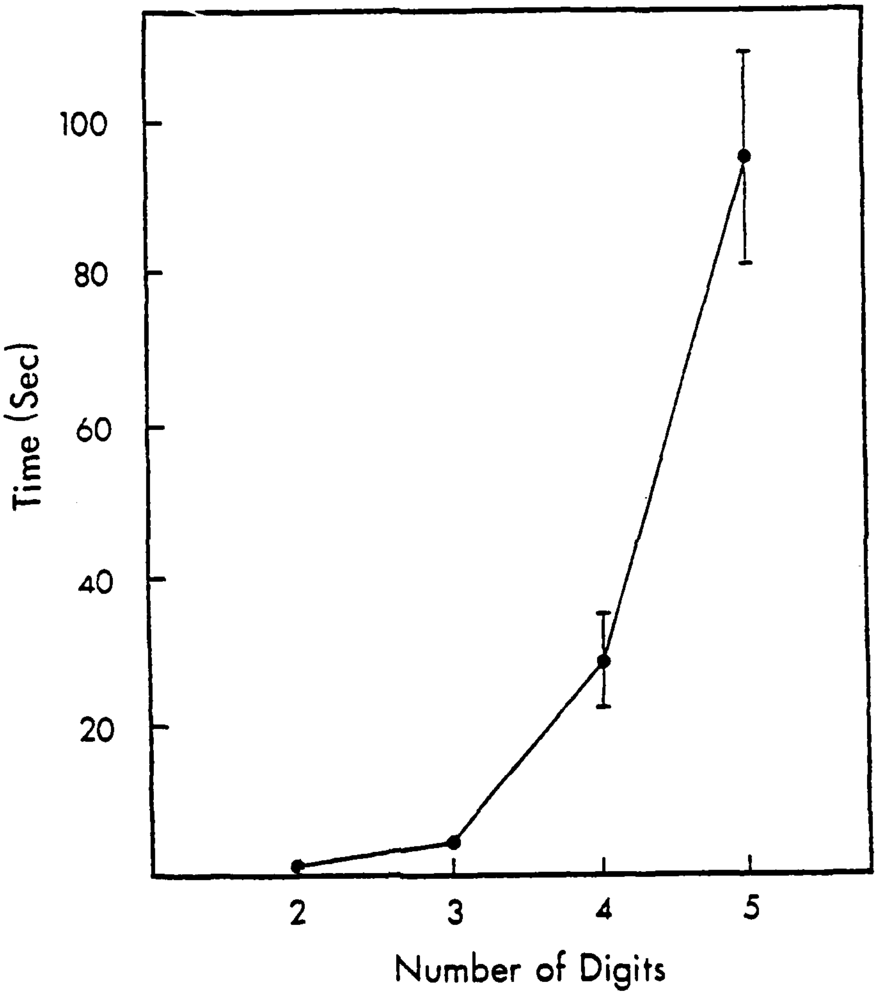
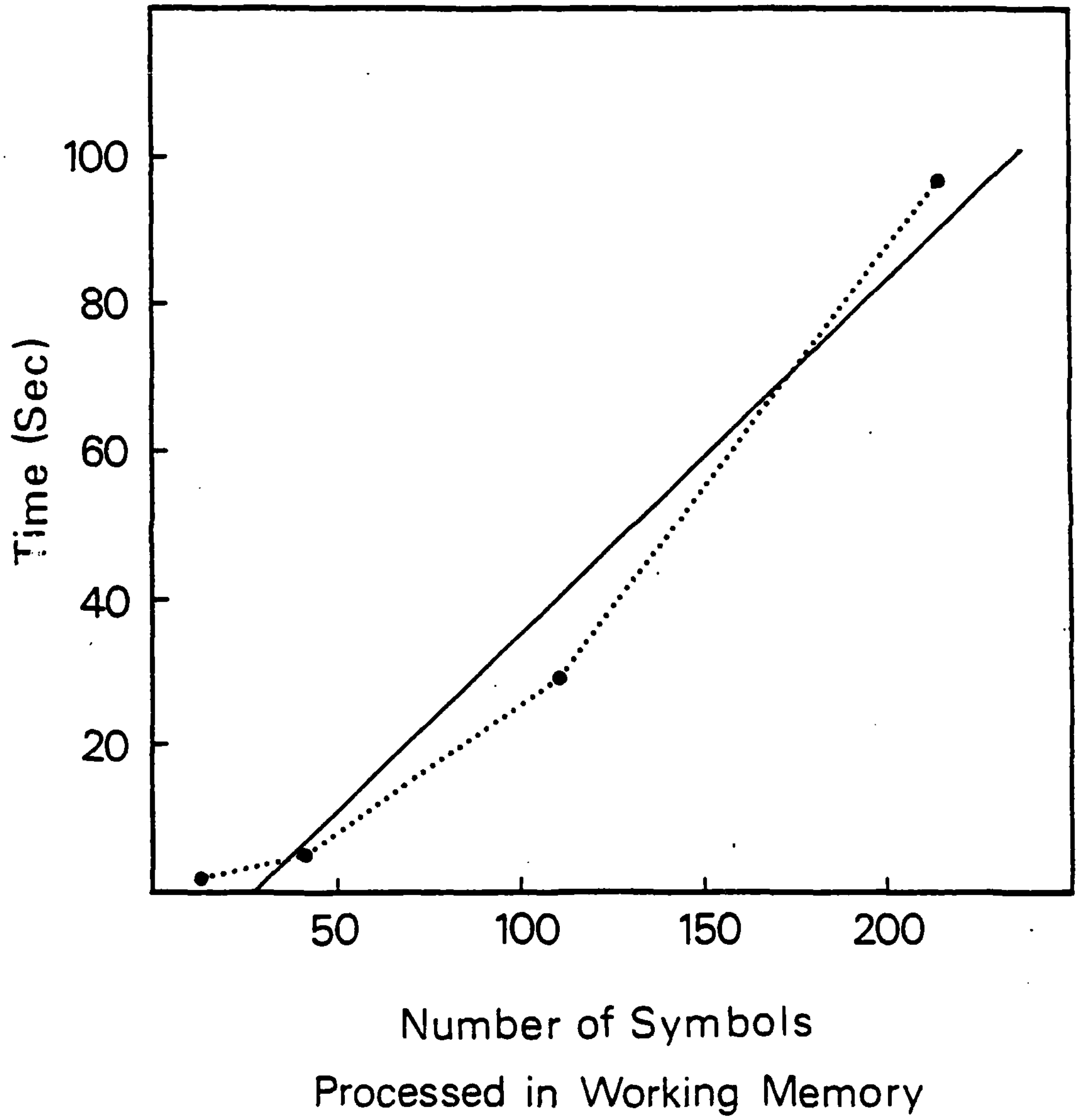


Figure 15



100
80
60
40
20
Time (Sec)
50
100
150
200
Number of Symbols
Processed in Working Memory

Figure 16

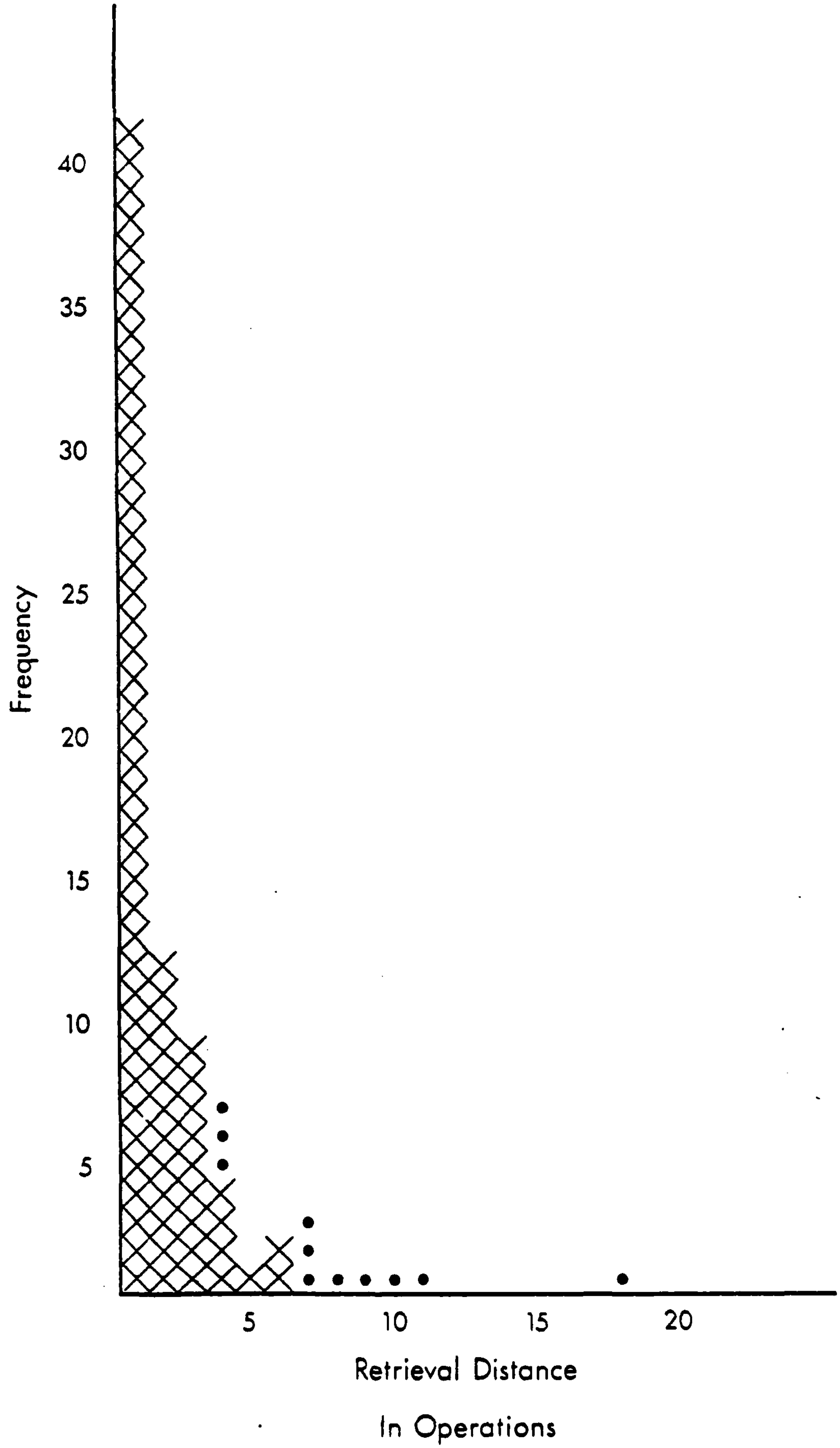

Frequency
40
35
30
25
20
15
10
5
5
10
15
20
Retrieval Distance
In Operations

Figure 17

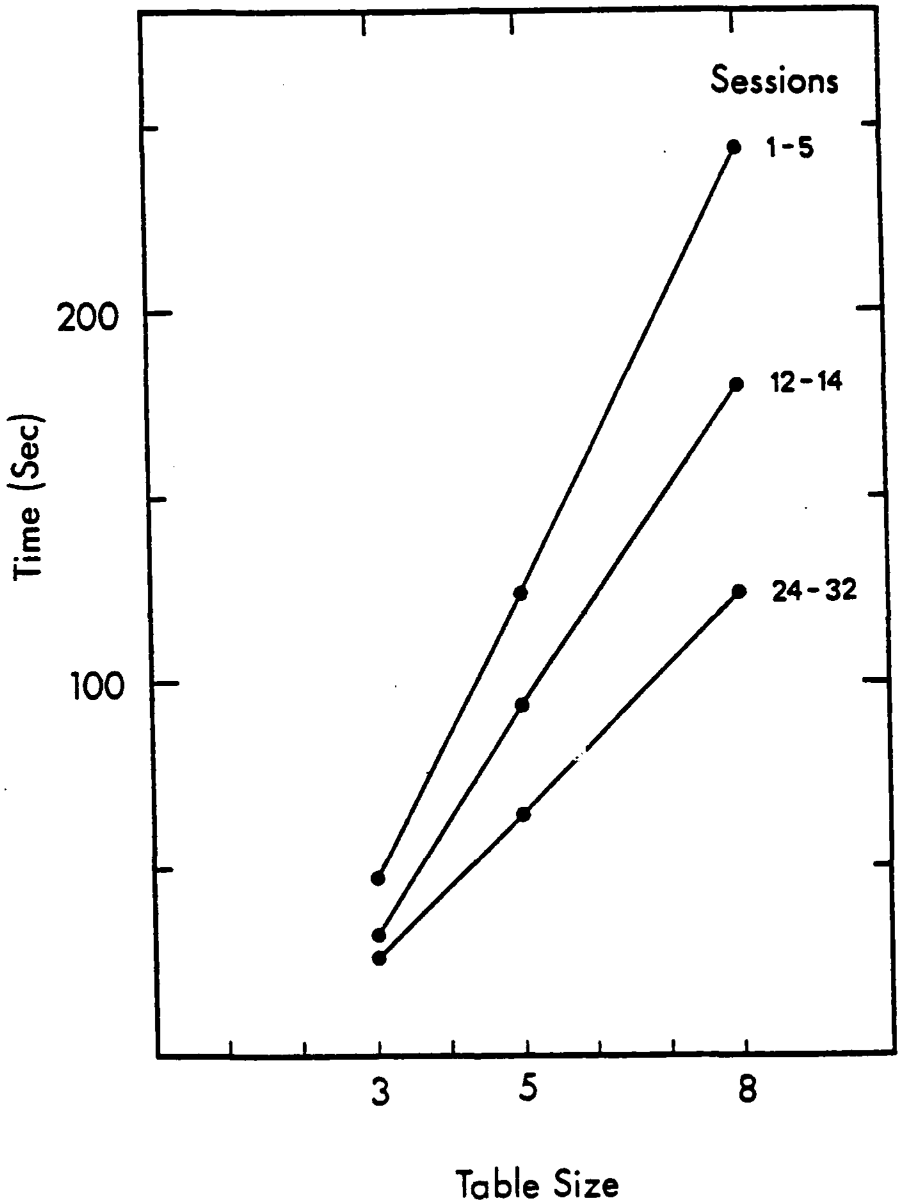


Figure 18

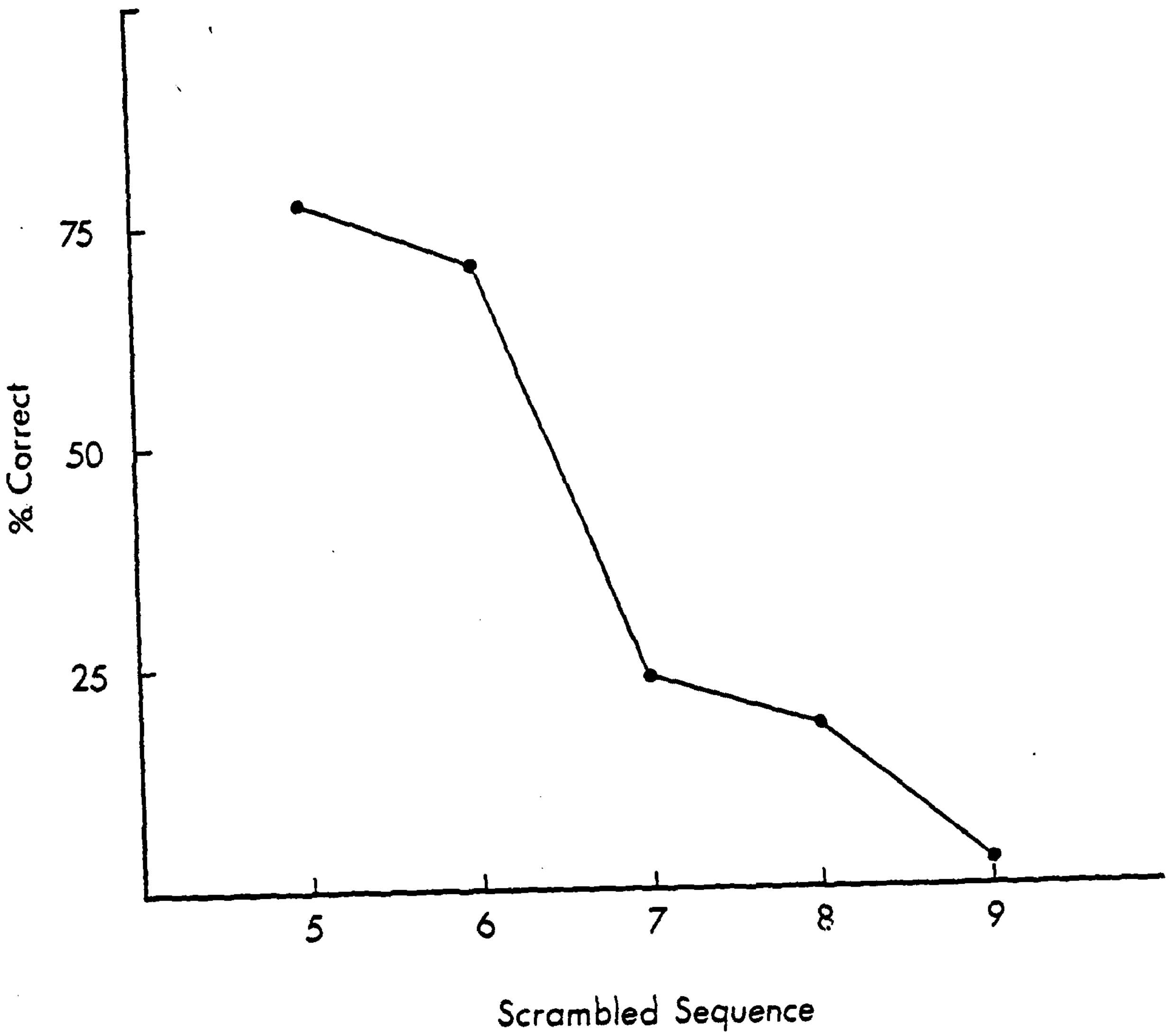


Figure 19

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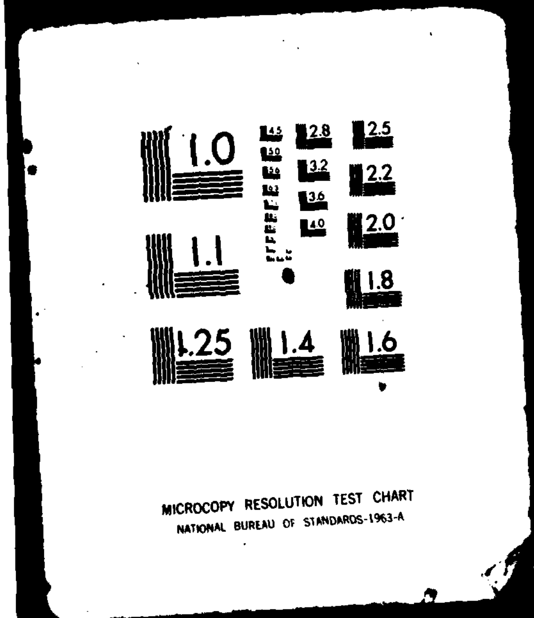

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